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GEOLOGY AND BIOLOGY OF PENNSYLVANIA CAVES

dited by William B. White

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES
BUREAU OF
TOPOGRAPHIC AND GEOLOGIC SURVEY
Arthur A. Socolow, State Geologist

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General Geology Report 66

GEOLOGY AND BIOLOGY OF PENNSYLVANIA CAVES

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PREFACE

This volume is intended to serve as an introduction to a new series of reports on caves of Pennsylvania, which was initiated in 1975 with the publication of General Geology Report 65, *Caves of Southeastern Pennsylvania* (edited by J. R. Reich, Jr.). Several other regional surveys in progress, including *Caves of Western Pennsylvania* (General Geology Report 67, 1976; edited by W. B. White) and two manuscripts dealing with caves of the Ridge and Valley and Great Valley sections of the commonwealth, should provide the interested speleologist with the most current information available on caves throughout Pennsylvania.

In this report three major papers deal with general cave geology and the faunal evidence recovered from several cave deposits. A wealth of new data has been generated concerning cave formation and development. New theories, utilizing this data have been proposed and much of this has been included. In addition, paleontological evidence reveals much about the types and diversity of the animal life as well as indicating climatic trends during Pleistocene time.

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ORGANIZED CAVING

Those who pursue recreational caving as a pastime of more than passing interest may find it to their advantage to contact either the National Speleological Society or its local chapters (known as "Grottos"). Local caving chapters can be of assistance in teaching advanced skills such as rope techniques for vertical caves, safety and safe caving methods, proper conservation practices, and can advise of delicate landowner situations.

To contact the national organization write:

National Speleological Society
1 Cave Avenue
Huntsville, Alabama 35810

At this writing there are six active Grottos in Pennsylvania: Lehigh Valley Grotto, Nittany Grotto (Pennsylvania State University), Philadelphia Grotto, Pittsburgh Grotto, Reading Grotto, and York Grotto. Three of these have established permanent mailing addresses which are

Nittany Grotto
P.O. Box 676
State College, Pa. 16801

Philadelphia Grotto
Box 2323
Philadelphia, Pa. 19103

Pittsburgh Grotto
Box 7565
Pittsburgh, Pa. 15213

Current addresses for the other grottos may be obtained from the National Society.

TO THE EXPLORER

It is vital for you to recognize that your fate and the fate of caving as a sport in Pennsylvania depend on the following three principles.

1. MOST CAVES ARE ON PRIVATE PROPERTY. Caves belong to the landowner. You should visit them only with his express consent and permission. You are in his cave as his guest. Many caves in Pennsylvania are off-limits to all because of the thoughtless discourtesies of a few in the past.
2. CAVES ARE DELICATE. The fragile beauty of the underworld can be destroyed with a few careless movements. Litterbugging in caves is no more to be tolerated than it is in parks and woodlands.
3. CAVES ARE DANGEROUS. Sport caving is practiced by thousands throughout the United States with great enjoyment. However, inadequate equipment or overextension of your skills can lead to accidents even in "easy" caves. Pennsylvania's single caving fatality occurred in one of the safest caves. Be careful.

THE GEOLOGY OF CAVES

by

William B. White

INTRODUCTION

It has been the custom to forward state cave surveys with an introduction to the geological principles of cave development, the relation of caves to the geological history of the region, and a description of the features to be found in caves. This introduction to the revised series on caves of Pennsylvania is in several parts. In the present section there is a general review of the geological aspects of caves, their forms and patterns, their features, and a review of theories of cave origins. Specific discussion of the geological setting of the caves of each physiographic province is given with the cave descriptions in the regional volumes.

A number of textbooks and review monographs are tabulated in the bibliography. The two newest works in English are by Jennings (1971) and Sweeting (1972). Another common reference work is Cullingford's *British Caving* (1962), although the emphasis is naturally on British caves. A very stimulating work on an elementary level is Moore and Nicholas' (1964) *Speleology*. Other reviews and summaries appear in the cave survey volumes of which one of the most complete is by Davies (1958) in *Caverns of West Virginia*. A recent important monograph provides review articles on many of the important karst areas of Europe, Asia and North America (Herek and Stringfield, 1972).

The material in the present review comes from a variety of sources. Some is from the original literature. Some is from a short course on cave geology taught at the 1968 National Speleological Society Convention at Springfield, Missouri. Much of the material on the classical theories of cave origin is taken verbatim from a review written some years ago* and is here published formally for the first time.

DEFINITIONS

What is a cave? Stone (1953) says, "A cave is a natural cavity beneath the earth's surface, whose dimensions are measurable in feet, whose walls are bedrock, and usually extending to absolute darkness." If not taken too literally, this definition will serve to convey the con-

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**Speleogenesis, The Netherworld News,* v. 6, p. 273-289 (1958) and v. 7, p. 6-26 (1959).

cept of "cave." In most literature the word "cavern" is used interchangeably. This means that in considering the origin of caves, we must consider all types of natural openings regardless of the rock in which they are formed or the types of forces that produce them. Included in this collection are sandstone shelter caves, lava tubes, and complex drainage systems in limestone.

The definitions used are distinctly anthropomorphic and present difficulties to those who would make statistical calculations on cave populations. Curl (1964) defines caves by specifying a minimum dimension which the cavity must possess. The length of the cave then becomes the distance which could be traversed by a sphere whose diameter was the specified minimum dimension (or module). Curl's definition allows a precise mathematical description of the statistical properties of caves.

CLASSIFICATION OF CAVES

Since caves, as seen from the viewpoint of the explorers, are primarily voids, a first requirement for description and interpretation is a genetic classification to separate the widely variant processes which generate voids. Many classifications have been proposed and the one given here is a composite of ideas expressed by Kyrle (1923) and DeBellard (1956), among others. We first separate caves into two broad classes: those that are formed by essentially chemical processes and those that are formed by mechanical processes. Within each class the caves are listed by the major process which led to their formation.

I. Caves formed by mainly chemical processes:
   (Strongly dependent on the lithology of the host rock)
   1. Solution caves
   2. Lava caves
   3. Ice caves

II. Caves formed by mainly mechanical processes:
   (Essentially independent of the lithology of the host rock)
   4. Tectonic caves
   5. Eolian caves
   6. Sea caves
   7. Talus caves
   8. Caves formed by outwash and slumping (Erosion caves)

Solution Caves

Solution caves form by the removal of bedrock by circulating groundwater and by underground streams. The water transports the bulk of the rock material out of the cave in solution. Most rocks, even the highly soluble ones, contain a certain residuum of insoluble material which must be transported mechanically by the water. Most solution caves are in limestone. Less frequently they occur in dolomite or gypsum. Small caves form in massive salt deposits. The only requirement is that bedrock be soluble. Most caves in Pennsylvania occur in limestone and it is the limestone caves that achieve the largest sizes and contain most interesting and attractive mineral deposits. This review will deal almost entirely with solution caves.

Lava Caves

Lava caves form in pahoehoe basalt lava flows and are the result of moving streams of lava within an already solidified flow. In many instances, an outlet permits the draining of the tube and a conduit-like cave results. These can be of considerable length such as Ape Cave in Washington, more then 2 miles long. Many are single conduits but multi-level development is not uncommon. Lava caves occur in many volcanic areas of the United States. The details of their origin are not known, although it is clear from observations published thus far that quite complex histories are recorded in some caves. They also have unique features, including lava stalactites, which have little in common, except a superficial morphological similarity, to features of solution caves. For more details on the geology of these caves and a description of many lava caves see Halliday (1963).

Ice Caves

Ice caves are caves in ice. These occur in many glaciers throughout the world and form by the action of sub-glacial streams which emerge from the foot of the glacier. Ice caves consist of long elliptical tube conduits often with delicately sculptured walls. Exploration of these caves is difficult since they are often completely flooded during part of the day and are only accessible when the water freezes at night. Explorations for distances to several miles have been conducted.

Ice caves should not be confused with *glacieres,* or freezing caves which are simply rock caves of some sort which contain perennial ice. The term "Ice Cave" in most American writings refers to this latter type of cave.

Tectonic Caves

Tectonic caves are formed by actual movement of masses of bedrock. They can occur in any type of rock, but are usually associated with hard insoluble rocks, because in insoluble rocks they are more easily distinguished from caves of other origins. The type of bedrock movement is not specified. It might be slippage along bedding planes, parting because of intense folding, or a sudden splitting due to faulting. Tectonic caves are usually small, but examples are known that run into hundreds of feet of passage. Dravosburg Cave in the Morgantown sandstone, Blessing Mountain Wells in the Pocono sandstone, Panther Cave in the Catskill shale, and Wind Cave in the Peters Creek schist are Pennsylvania examples. One does not usually classify limestone caves in this group, but work on the caves in the Dachstein massif indicates that even in limestones a tectonic theory may be applicable (Groom and Coleman, 1958).

Eolian Caves

Eolian caves are formed by the abrading action of wind-borne particles. They are common to desert regions where soft sandstones often have small caves carved into them. Caves which are apparently due to wind action have also been reported in loess.

Sea Caves

Sea caves (also called "Littoral Caves" in some literature) are formed by the milling of sea coasts by wave action. They occur in many coastal areas throughout the world. Some of the most famous caves known are sea caves of which Fingal's Cave in the Hebrides Islands and the Blue Grotto on the Isle of Capri are two examples. While some sea caves have formed along the rocky New England coast, the mid-Atlantic and southeast coasts of the United States are unsuitable for development of sea caves because of the low relief of the Coastal Plain. The West Coast in California, Oregon, and Washington abounds with sea caves in a variety of rocks. Descriptions may be found in the California and Washington Cave Surveys (Halliday, 1962, 1963).

Talus Caves

Talus caves are formed when masses of piled boulders or other rock debris arrange themselves in such a way as to leave explorable openings beneath and between the blocks. These caves are only of interest if they reach considerable size. Obviously, there are indefinitely large numbers of small openings in all boulder slopes. In a few instances talus caves in sandstone and granite have interconnected passages of large extent. The "ice caves" at Colerain and Trough Creek State Parks are talus caves in scree slopes of sandstone blocks.

Erosion Caves

For lack of a better name we use "erosion caves" to describe two types of minor openings both formed by mechanical erosion of soft rock material. One type is the soil pipe or pit formed by outwashing of soil or soft rock material by stream action. These are uncommon in Pennsylvania but occur in badland type areas in arid climates. The second type is the typical Pennsylvania rock shelter which forms when a resistant sandstone layer overlies a weaker shale horizon. Often small sandstone cliffs occur where minor streams flow down steep hillsides. The underlying shales are easily undercut and a combination of slumping and erosion cuts the shale back leaving a sandstone overhang. While the rock shelters formed in this manner would not usually be considered to be caves, they are often referred to as caves locally, sometimes appear on maps as caves, and are often listed as cave sites by archeologists or historians who are concerned with the human usages of such shelters. The Sheep Rock in Huntingdon County, an archeological site, and Christopher Gist Cave in Fayette County, of historical interest, are two examples.

KARST TOPOGRAPHY

The term karst describes a landscape of characteristic landforms and subsurface features produced primarily as a result of solution of the underlying bedrock. The solution process is accompanied by other processes, particularly slumping of soil and bedrock materials, transport of insoluble debris through subterranean routes, and some mechanical wasting of slopes. Karst features form on many types of rock if soluble components are present. Karsts on limestone are most commonly described, although extensive karsts occur on gypsum, salt, chalk, clastic rocks with soluble cements, and indeed any rock on which the solution process can act.

The suites of landforms vary from region to region depending on the local geology, relief, and climate. The most extensive karst development occurs in regions where thick, massive limestones are exposed above base level and there is high relief to provide a hydraulic gradient for the water. Some of the most spectacular karst in North America occurs in Mexico and in the Caribbean Islands, Cuba, Puerto Rico, and Jamaica.

Karst in tropical climates tends to take the form of steep-sided residual hills with intervening deep sinkhole valleys with no surface outlets. The relief from hilltops to sink bottoms may be several thousand feet. Some residual hills such as the "mogotes" of Cuba are nearly vertical-walled towers rising hundreds of feet above the surrounding plain.

Karst in arctic and alpine regions tends to consist of bare limestone rock, scoured in places into a flat pavement perhaps by the action of glacial ice. Joints and fractures are widened by solution and deep linear crevices are the common landform. Because relief is high in alpine karsts, underground features tend to be deep pits and shafts which may reach depths of more than 1000 feet.

In regions of temperate, moist climate such as Pennsylvania, karst features tend to be subdued. The most characteristic landform is the sinkhole or doline. Surface drainage is often underground so that sinking streams, underdrained valleys, and big limestone springs are the common hydrological features. There is some sculpturing of the limestone surfaces, but the details of these features are usually obscured by the overlying soils. We shall be concerned in the section that follows only with the temperate climate landforms. For a much more comprehensive description and discussion see the books by Jennings (1971) or Sweeting (1972).

We are now in a position to place the karst regions of Pennsylvania in their correct perspective. The commonwealth has two principal karst regions, the Cumberland Valley and the Nittany Valley (Figure 1). Other smaller karst regions exhibit features similar to these two. Both are on highly folded limestones. Both have thick soil mantles. Only in the southern Cumberland Valley are the limestone ledges exposed above the soil. Both valleys are mainly a subdued doline karst with the dolines rather sparsely scattered over rolling valley floors. There is considerable evidence for solutional modification of the bedrock surface beneath the soil mantle. Dry valleys, blind valleys, and underground drainage are frequent in occurrence but limited in extent.

The Cumberland Valley is the northern terminus of the great limestone valley that extends southward as the Shenandoah Valley of Virginia on through east Tennessee. With a total length of more than 500 miles, the Great Valley is one of the greatest karst valleys in the world. The Valley and Ridge Province with its limestone-floored valleys can likewise be traced through West Virginia and southwestern Virginia and into Tennessee. Some considerable changes occur in the southern part of this karst province. In Pennsylvania the limestone outcrop is limited to the valley floors. Farther south it crops out higher on the mountain ridges and the type of cave and karst landform changes accordingly. The tiny trace of plateau karst in the flat-bedded rocks of western Pennsylvania is only the northern tip of an extensive karst that extends southward as the Plateau Karst of West Virginia on the Greenbrier limestone. Farther south the same province contains the Cumberland Plateau karst and caves of central Tennessee and northern Alabama. The Pennsylvania karst areas therefore are samples of each of the major karst regions that make up the Appalachian Mountain karst, one of the most extensive in the world but perhaps the most poorly described.

KARST VALLEYS

Depending on the extent to which underground drainage is developed, a karst area may or may not retain evidences of fluvial processes

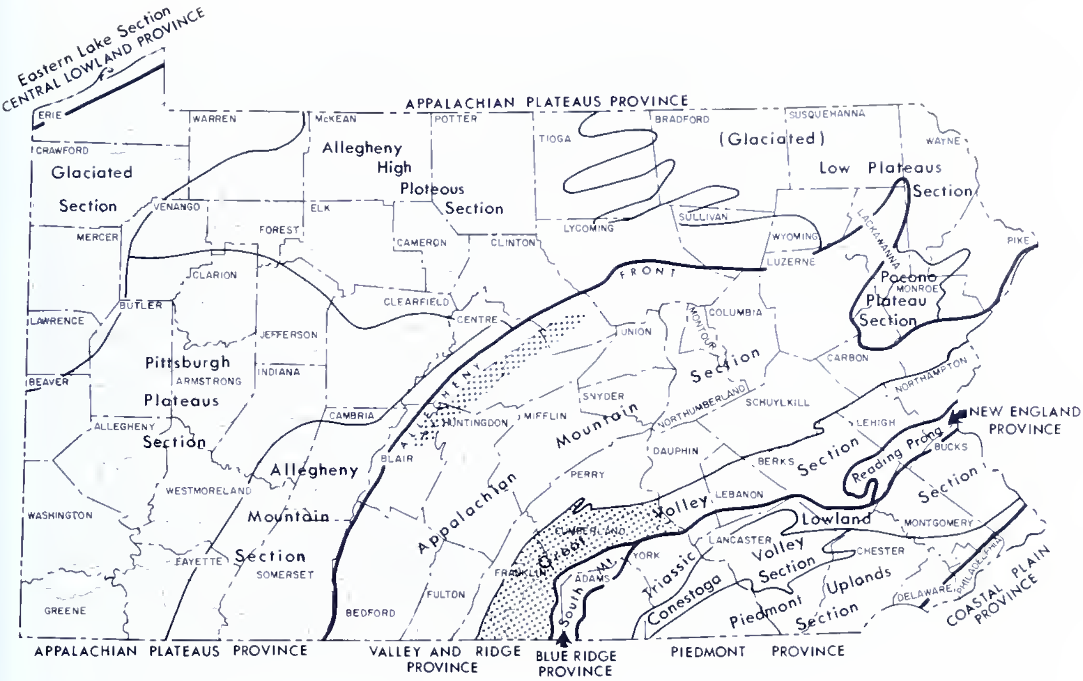


Figure 1. Physiographic province map of Pennsylvania with the Nittany Valley (central) and the Cumberland Valley (south central) shown in a dot pattern.

on the surface. Stream valleys, which may or may not contain present-day streams, and which contain superimposed karst features are called *karst valleys*. Some exist because surface drainage has never been pirated completely underground and fluvial erosion has been able to maintain itself. Others form because the pattern is superimposed from stream valleys developed on overlying clastic rocks which are later eroded away, exposing the underlying limestone. These may retain the pattern of a stream valley but quickly lose their profiles through loss of water and subsequent destruction of the stream channel.

Two main valley patterns may develop, depending on the way in which the original surface stream lost its water. *Dry valleys* are simply those in which the surface stream has gone underground. *Blind valleys* are those in which for some period the drainage was underground in one reach of the valley and on the surface in another reach, thus forming either a blind headwall from which the stream emerged as a spring or a blind footwall into which the surface stream sank.

Dry valleys exist in all stages of development. Some, which may be referred to as *semi-dry valleys,* retain well-developed stream channels through which the stream flows over the surface during high run-off periods. The next step is for the stream to remain dry the entire year and to flow only during exceptional floods. In a humid temperate climate with good soil cover such as in Pennsylvania, the stream channel quickly degenerates and a stage is reached when little trace of the stream bed remains. Advancing karstification may then degrade the valley walls so that with extensive doline development, all traces of the former fluvial history of the area may be obliterated.

Blind valleys are more likely to develop where streams either enter or leave a karst area. Streams flowing from karst regions often occur in steep narrow valleys incised well below the general level of the terrain. They have their sources in large springs flowing from the bottom of the blind headwall of the valley. Mammoth Spring, which forms the head of Honey Creek in Mifflin County, is an example. Most of the karst areas in Pennsylvania are bordered by clastic rocks. This is particularly true in the Valley and Ridge Province where streams flow from the sandstone and shale underlying mountain sides and sink at the contact with the limestone in the valley. These mountain streams often cut deep narrow gorges, really too small to be called valleys in most cases, into the limestone and sink at the base of the blind limestone cliff that cuts off the lower end of the gorge (Figure 2).

Brush Valley in Centre County provides examples of most karst valley features. Two creeks carry water from the valley, Elk Creek

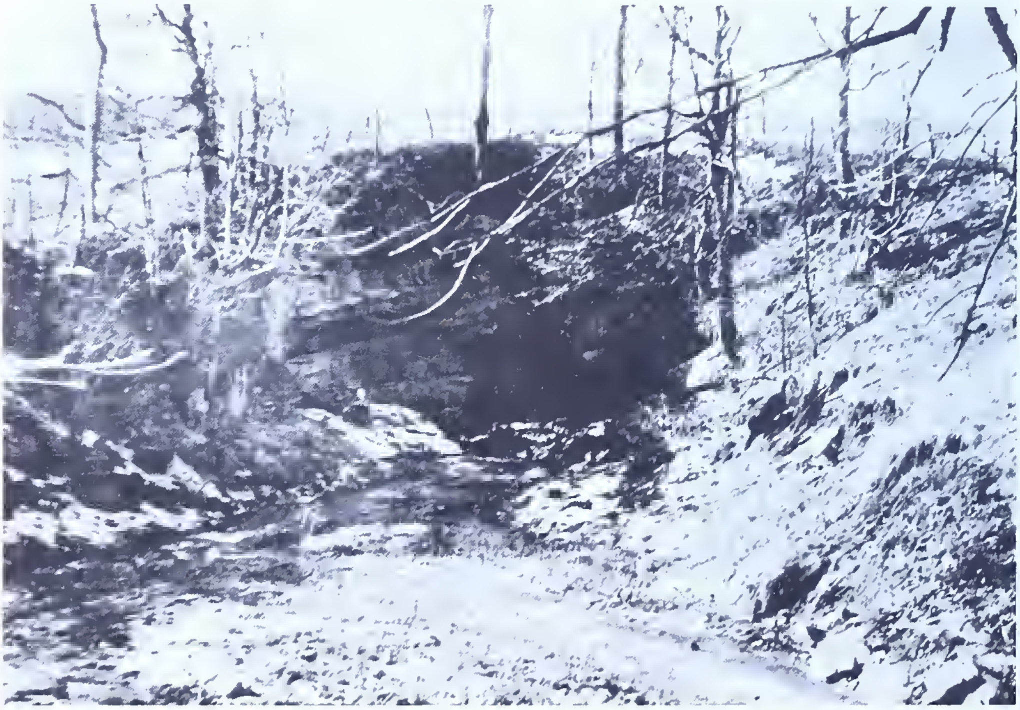


Figure 2. Laurel Creek flowing into a sinkhole in Mifflin County.

which heads in a large spring and flows through a water gap in Brush Mountain near the middle of the valley, and Penns Creek which heads in Penns Cave at the western end of the valley (Figure 3). Brush Valley is cut off by mountains at its eastern terminus but is open into the wider Penns Valley at the western end. The main surface stream in the valley is Elk Creek, which flows from the eastern mountains along the valley for some four miles before it sinks through small openings in a limestone ledge. Downstream from the swallow hole, the dry bed of Elk Creek continues for an additional mile to the Elk Creek rising, below which the stream again flows on the surface. The surface route is utilized for flood overflow every spring. Between the gap where Elk Creek leaves the valley and Penn's Cave, there is little trace of the surface stream. This portion is a dry valley in the complete sense. Dozens of small mountain streams enter Brush Valley from both sides. All sink at or near the limestone contact as short blind tributary valleys.

When further degradation of the valley begins to expose the karst stream to the surface again quite complicated patterns can develop. Sinking Creek in Sinking Valley, Blair County, has alternate stretches of surface and underground flow with many risings and sinkings. Where exposed as a surface stream, Sinking Creek often flows in a deep limestone canyon incised below the average level of the valley floor. Fragments of the underground route are left behind as caves or occasionally as *natural bridges* of which the arch at Arch Spring, the final rising of Sinking Creek, is Pennsylvania's most scenic example (Figure 4).

CLOSED DEPRESSIONS

Perhaps the most characteristic landform of a karst region is the circular or nearly circular closed depression with interior drainage. These are found in a scale of sizes from features a foot or so across to the gigantic poljes of the Adriatic Karst whose diameter is measured in tens of miles.

Dolines, or sinkholes as they are commonly labeled in the United States, are depressions in the bedrock below the general level of the land surface. Most dolines in temperate climates are draped with soil and give the landscape a pockmarked appearance (Figure 5). They may have no surface expression if they are completely soil-choked but are visible in quarry walls and highway cuts where the rock has been cut away to expose their cross-sections. Dolines arise from surface solution of the bedrock (solution dolines) and from collapse of underlying caverns (collapse dolines). If the soil mantle were removed the solution doline would appear as a funnel-shaped cavity in the bedrock sloping

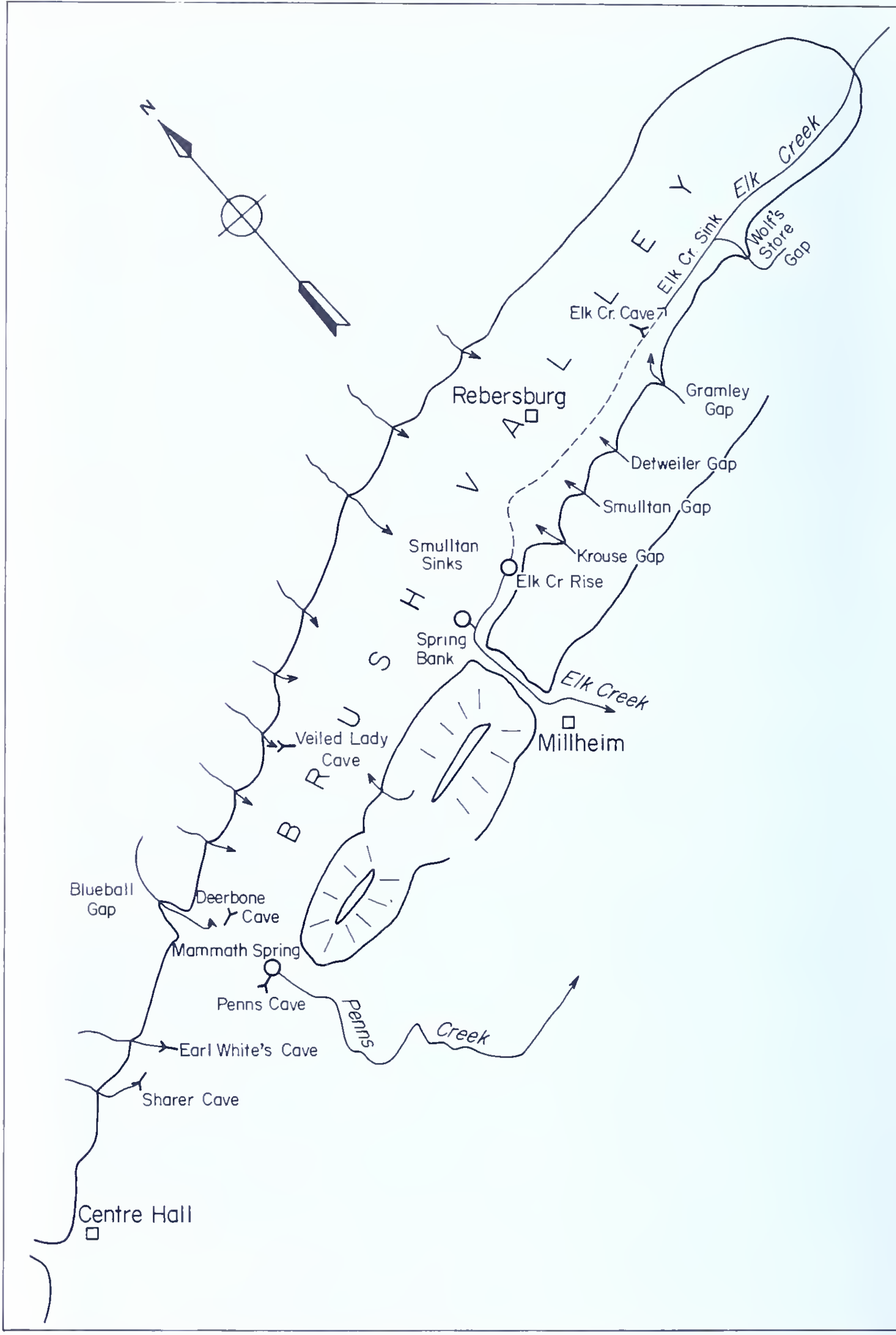


Figure 3. Diagrammatic sketch of Brush Valley showing numerous springs, caves and disappearing streams.

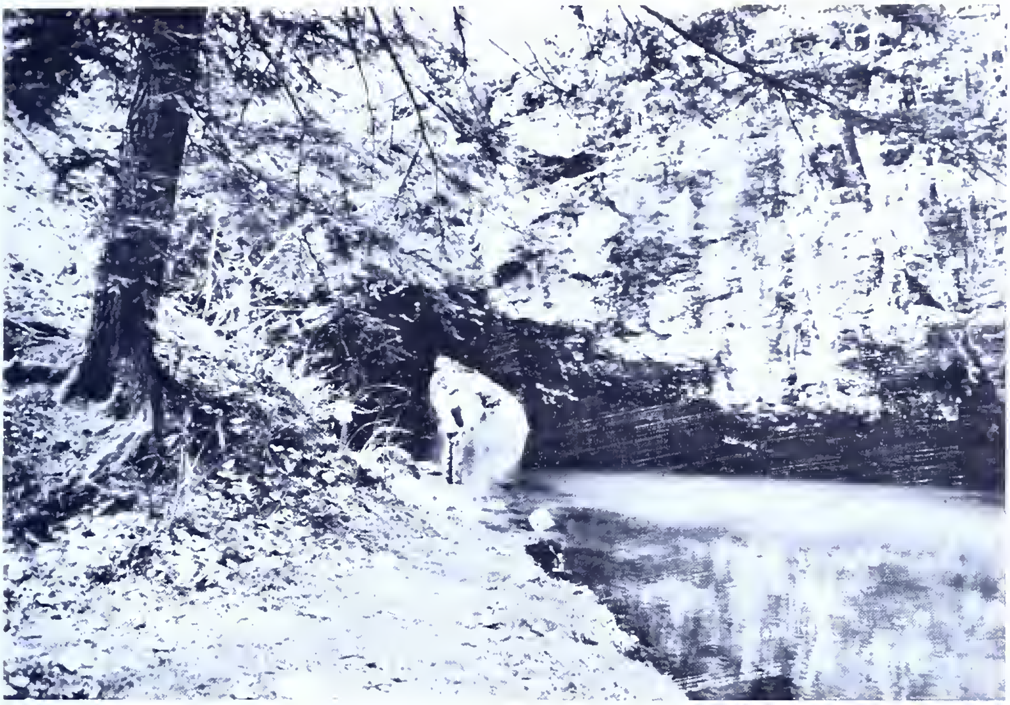


Figure 4. The natural bridge at Arch Spring, Sinking Valley, Blair County, Pennsylvania.

down to a small drain channel in the center. The collapse doline forms by failure of the bedrock ceiling of an underlying cave passage with subsequent stoping of rock and soil material into the cavity. Experience in Pennsylvania shows that these are useful end-member types but that in reality most dolines have elements of both solution and collapse in their histories and are indeed formed by a composite of the two processes. In addition there is little difference in the surface expression of the two sub-types because of soil inwash and the collapse of the initially vertical walls of the collapse doline.

There is some evidence that the initial vertical path for descending groundwater is provided by one or more joints. This initial zone of weakness locates the doline. Some dolines form in more or less linear arrays because of joint control, but such structural control is not evident in all cases. Some Pennsylvania dolines have complicated patterns. The entrance sink to Indian River Cave in Blair County is a large doline which exposes the cave entrance, and a spring from which Sinking Creek rises and flows across the doline floor into the cave mouth. This feature is known as a *karst fenster*. The entrance sink to Tippary Cave, Huntingdon County, is a vertical-walled doline 75 feet deep with sheer walls. It lies almost on the line of the Yellow Springs Fault. Shattered rock from faulting provided the zone of weakness for

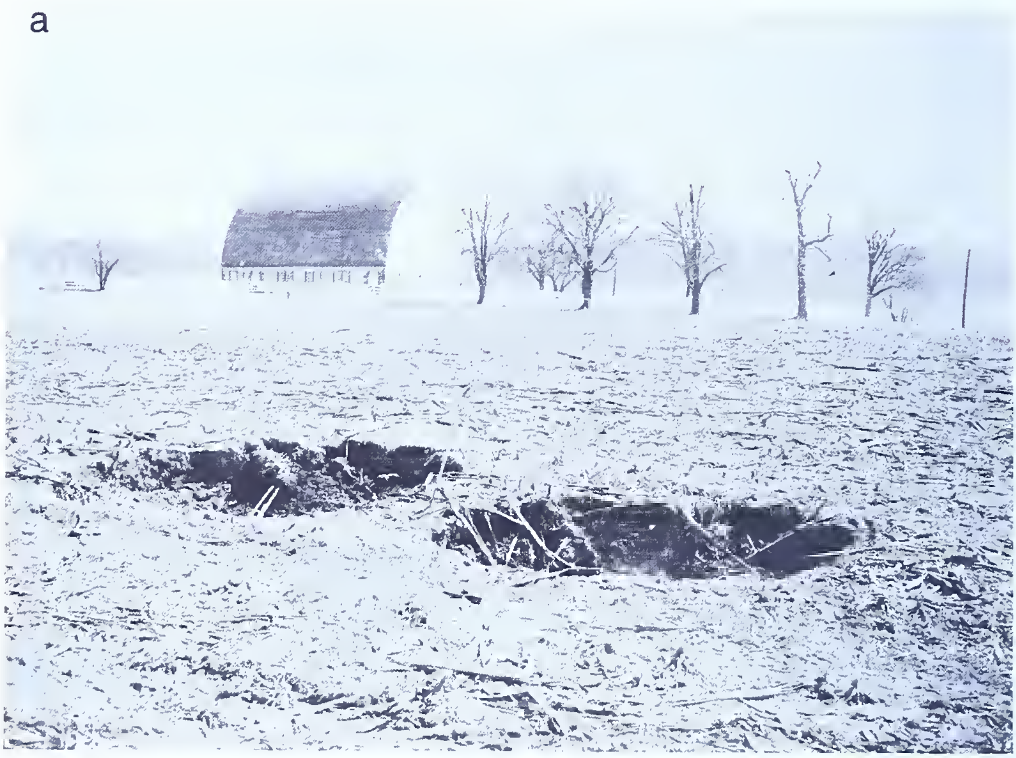
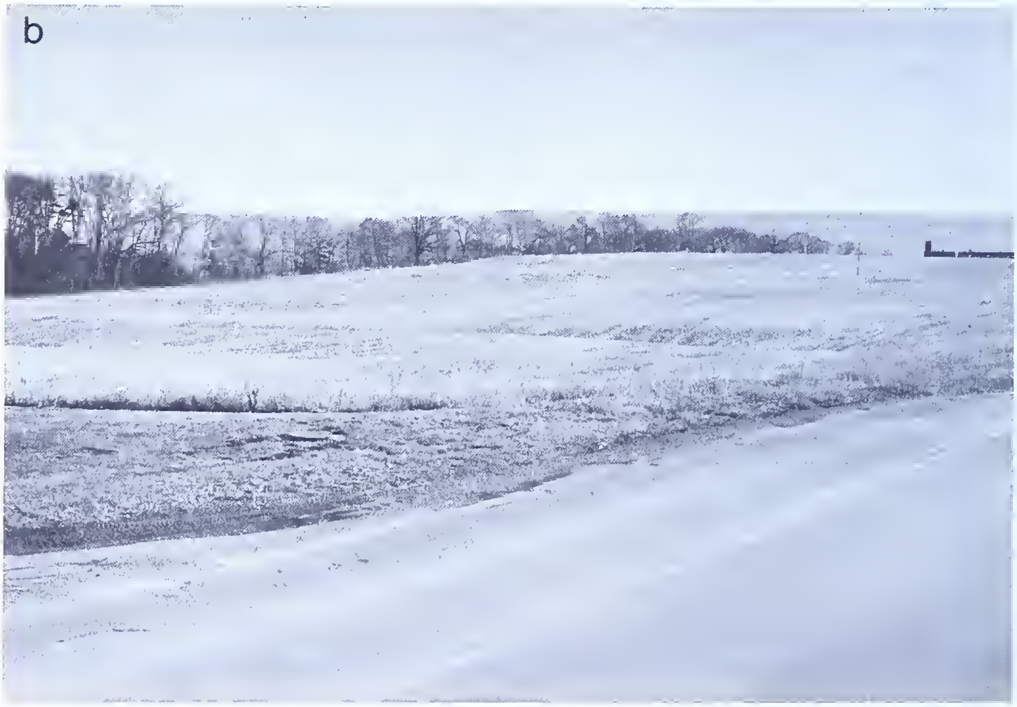


Figure 5. a. Sinkholes in the Great Valley region, Derry Township, Dauphin County. b. Less obvious but still detectable dolines in the Ridge and Valley region of central Pennsylvania.



vertical solution. In each of these examples both solution, collapse, and stoping from below have contributed to the final form of the doline.

In areas with extensive expanses of massive horizontally bedded limestones, doline development is enhanced and we find many square miles of doline karst (known in the United States as "Sinkhole Plains"). The density of dolines is very high. Often the dolines touch or overlap with little or no flat ground in between. Examples occur in Greenbrier County, West Virginia, the Mitchell Plain of Southern Indiana, and the Pennyroyal Plain of south-central Kentucky.

The formation of collapse features is one of the most important aspects of carbonate terrains from the point of view of regional planning or land use management. Sinkholes form naturally but the process can be greatly accelerated by the actions of man. Lowering groundwater levels by pumping will drain the soils that fill existing solution cavities, decrease their load-bearing capacity, and cause slumping and subsidence. It will also increase hydraulic gradients leading to increased velocities of storm water runoff into sinkholes, and more effective removal of soils, leading to more collapse. The limestone roofs of caverns may have poor load-bearing capacity and a cave roof that is stable under natural conditions may collapse if a highway or building is constructed on it. Paving of sinkhole areas leads to concentrated runoff and intensive erosion of soils and weathering and weakening of bedrock where the drainage from parking lots, streets, and roofs is discharged into the limestone.

SOLUTIONAL SCULPTURING OF THE LIMESTONE SURFACE

When a limestone surface is exposed to weathering by solution, the rate at which the rock is removed is a very sensitive function of minor variations in lithology, and defects in the rock structure (joints, bedding planes, vugs, and irregularities in the bedding) as well as of the hydraulics of the water movement across the rock surface and the presence or absence of a soil cover. The interplay of all these factors produces an astonishing variety of minor relief features on the limestone surface. These small landforms as a class are referred to as *karren* or by the French term *lapies*. Extremely complicated classifications and nomenclature for the karren features have been proposed. Descriptions and interpretation may be found in papers by Bögli (1960) on alpine sculptured forms and by Pluhar and Ford (1970) on karren forms in Ontario. See also the books by Jennings (1971) and Sweeting (1972).

The most important single factor in karren development is the presence or absence of a soil cover. A limestone surface weathered under a soil has somewhat more rounded features. Weathering of the bare bedrock, as occurs in alpine regions, results in sharper more pinnacle-like features. Sub-soil karren *(Boden-karren)* are more common in Pennsylvania where the relief is less and soils are thick. The true karren surface is thus rarely seen except in quarry walls and road cuts and in exceptional cases where the soil has been removed.

Most important of the various karren forms is the solutionally widened joint. These occur in all climates, with and without soil cover, and in all soluble rock types. The only requirement is some line of weakness, a joint or fracture to focus the solutional attack. The size of these features varies over several orders of magnitude from narrow fissures an inch or so wide and a few inches deep to tens or hundreds of feet wide.

The principal type of karren in the Cumberland Valley Province of Pennsylvania, particularly in Franklin County and south into Maryland takes the form of parallel bands of exposed limestone ledges with intermediate deep soils. Excavation reveals that the intermediate soils are filling crevices dissolved into the bedrock often for depths of tens of feet. The crevices are parallel to the strike and appear to form along open strike joints. The exposed ledges of limestone are etched into small grooves, runnels, and pinnacles. Howard (1963) gives an excellent discussion of the origin of these features and refers to them as cutters.

CAVERN FEATURES

In the sections that follow we shall be much concerned with the origin of caves and the minerals and sediments that occur in caves. It is necessary, therefore, to first consider the systematics of the caves themselves. Caves are voids. They are the regions where the rock has been removed. These voids have certain characteristic geometries and the walls of the void are often very intricately sculptured. It is the object of this section to describe the various shapes and morphologies of the cave passages and establish a nomenclature for the bedrock features found within.

CAVE PASSAGE PATTERNS

Most caves appear complex either viewed from inside or in map view. It becomes less difficult to understand this complexity if we use a building-block principle to describe the cave. Caves are made of *passages*. The passages have various shapes, various relationships to each other, may have formed at the same or at different times, may have been formed by a single water source or by different sources. Passages in the same cave may be genetically related or only fortuitously connected. We first describe the cave passages and later show how these interconnect to form caves.

The pattern or map view of an individual segment of cave passage will be determined by the structural and stratigraphic factors controlling the route followed by the moving groundwater. End-member types are illustrated in Figure 6.

A *linear* pattern is simply a straight reach of passage without bends. Linear caves occur in the Valley and Ridge province and nearly always appear oriented along the strike in steeply dipping limestones.

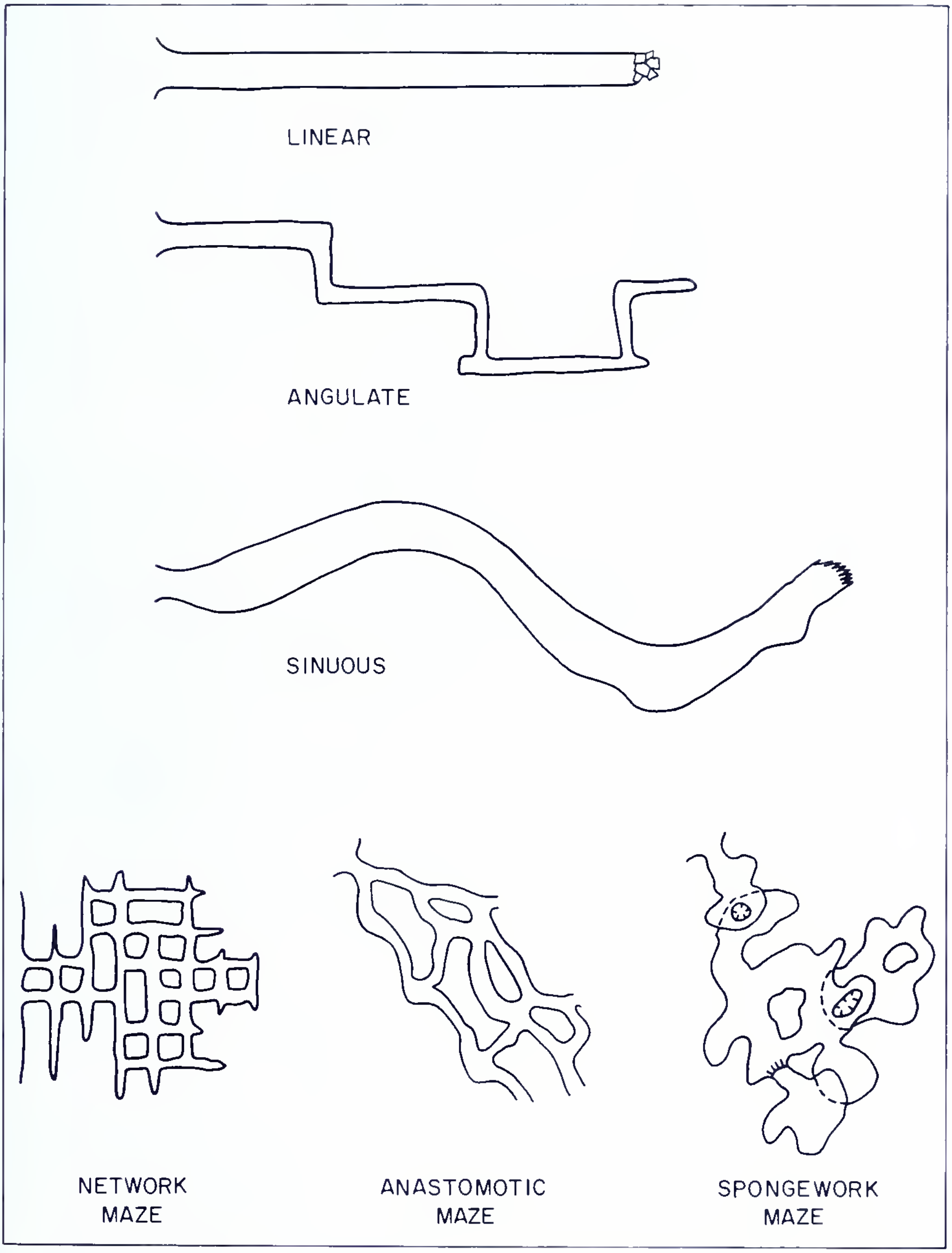


Figure 6. Plan view of several basic types of cave-passage patterns.

Angulate patterns (called rectangular by White, 1960) are good evidence for some sort of joint or other structural control. In regions of dipping limestones, long reaches of the passage may be oriented along the strike while the short segments cut across the bedding. These patterns also develop in flat-bedded limestones where presumably the hydraulic gradient was oriented diagonally to the regional joint set. The groundwater flow used first one set and then the other to carve a zig-zag course through the joint blocks. In the few cases that have been measured, the rosettes of orientations of the angulate cave passages have been found to parallel the rosettes of the joint system for the area.

Some passages, particularly in regions of flat-bedded limestones where long conduit-like caves are common, have a *sinuous* pattern. Instead of sharp angle bends with straight stretches of passage between bends, the sinuous passage has broad sweeping curves and relatively few really straight reaches of passages. Passages with this pattern have at least a superficial resemblance to meandering surface rivers. Deike and White (1969) plotted the bend spacings of a large number of sinuous cave passages as a function of passage width and found that the relation of bend spacing to passage width in sinuous caves was very similar to that for surface rivers.

A cave consisting of a highly interconnected set of passages can be said to exhibit a maze pattern. The labyrinthine character of the maze cave is the result of simultaneous, rather than sequential, enlargement of joints, bedding plane partings, or other routes of groundwater movement. Thus, we consider it to be a single passage element just as the other patterns were considered single passage elements. It might be regarded as the underground equivalent of a braided river.

In a recent study Palmer (1975) has distinguished three sub-types of maze pattern:

(i) *Network mazes* consist of an angular grid of intersecting fissures that form by solutional widening of nearly all major joints to roughly the same size openings.

(ii) *Anastomotic mazes* are formed of curvilinear tubes, typically of circular or elliptical cross section that intersect in a random or braided configuration.

(iii) *Spongework mazes* consist of interconnected, nontubular solution cavities of varied size and irregular geometry arranged in an apparently random, three-dimensional pattern.

Maze caves in Pennsylvania are mainly of the network maze type.

Network pattern caves usually occur in flat-lying limestones and the plan and spacings of the net are determined by the regional joint pattern. There is no reason why the network must occur at right angles, although rectilinear patterns seem to be the most common. In an ideally developed network, every joint is opened and the passage spacing is the same as the joint spacing. Brady's Bend Cave, Armstrong County, is one of the best examples.

PASSAGE CROSS SECTIONS

The cross section of a cave passage represents a compromise between hydrodynamic forces that tend to shape the passage into smooth streamlined forms, and the variations in solubility of the bedrock and the shape of the initial guiding joint or bedding plane which often generate more complicated shapes. We can, therefore, subdivide cross sections into those that are primarily determined by the flow hydraulics and those whose shapes are structurally determined. High velocities and thick uniform limestones tend to promote the hydraulic forms, while low velocities and non-uniform bedding and lithology enhance the formation of channels with complicated cross sections. Some of these are illustrated in Figure 7.

Mainly hydraulically controlled passages trend to two end-member types—the canyon and the elliptical tube. Canyons are typically

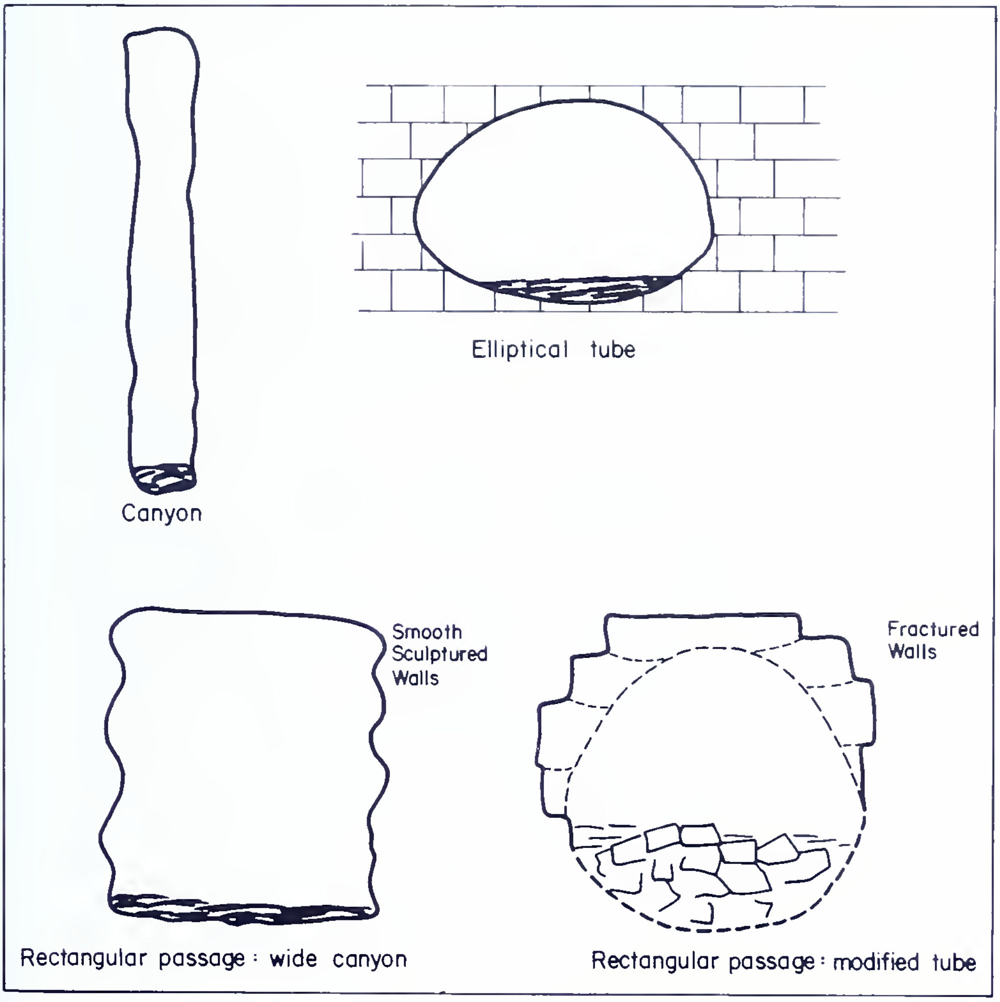

Elliptical tube
Canyon
Smooth Sculptured Walls
Fractured Walls
Rectangular passage : wide canyon
Rectangular passage : modified tube

Figure 7. Several cross-sectional passage shapes which have been controlled mainly by flow hydraulics.

higher than they are wide, have near-vertical walls with little variation in passage width, and may show evidence of fast-flowing water. Canyons are of at least two origins. They may be formed by small free-surface streams gradually downcutting through the limestone or by solutional widening of a very regular joint under phreatic conditions. The canyon shape itself is not a conclusive proof of the type of flow. Elliptical tubes are more or less regular pipes and presumably formed by groundwater flowing under pipefull conditions. These vary in size from tiny openings too small to enter, to perhaps 100 feet across.

An intermediate geometry is the rectangular passage also illustrated in Figure 7. It can form as a wide canyon in a flat-bedded sequence with a relatively insoluble roof bed, or it can form from an elliptical tube by breakdown of the projecting beds. Since both forms may be floored with an unknown depth of sediment, the origin of the passage may not be self-evident from casual examination.

Passages controlled by rock structure can be extremely complicated in cross section, depending on whether joints or bedding planes or both, were the primary groundwater routes. Dip of beds usually has a considerable influence (Figure 8).

In some caves a complex cross section occurs that is a combination of the various sections shown in Figure 9. These may be called *composite cross sections* or *composite passages*. A common form is the T-shaped passage with an elliptical tube at the top and a canyon cut into its floor. Sometimes there is a canyon in the ceiling with a tube below. Still more complicated combinations exist. The components of the composite passage are really independent passages. They overlap in one reach of the passage to give the composite cross section and diverge either upstream or downstream.

VERTICAL FEATURES

A remarkable aspect of most caves in regions of moderate-to-low relief is that the principal passages are either nearly horizontal or almost vertical. The vertical features may be conveniently divided into two types: *chimneys* and *vertical shafts* (Figure 10). Of the two, the vertical shafts are much better characterized and their geological relationships and mode of origin are better understood.

Vertical shafts were named by Pohl (1955) as a more precise designation for the common vertical feature of the central Kentucky karst region. Vertical shafts are cylindrical voids with vertical walls. In Kentucky, they range from 20 to 200 feet in height and to 50 feet in width. The base of the shaft is often a shallow basin in bedrock. The walls are often fluted. Shafts are formed by films of water moving down their sides at very high velocities (Brucker, Hess and White, 1972). A

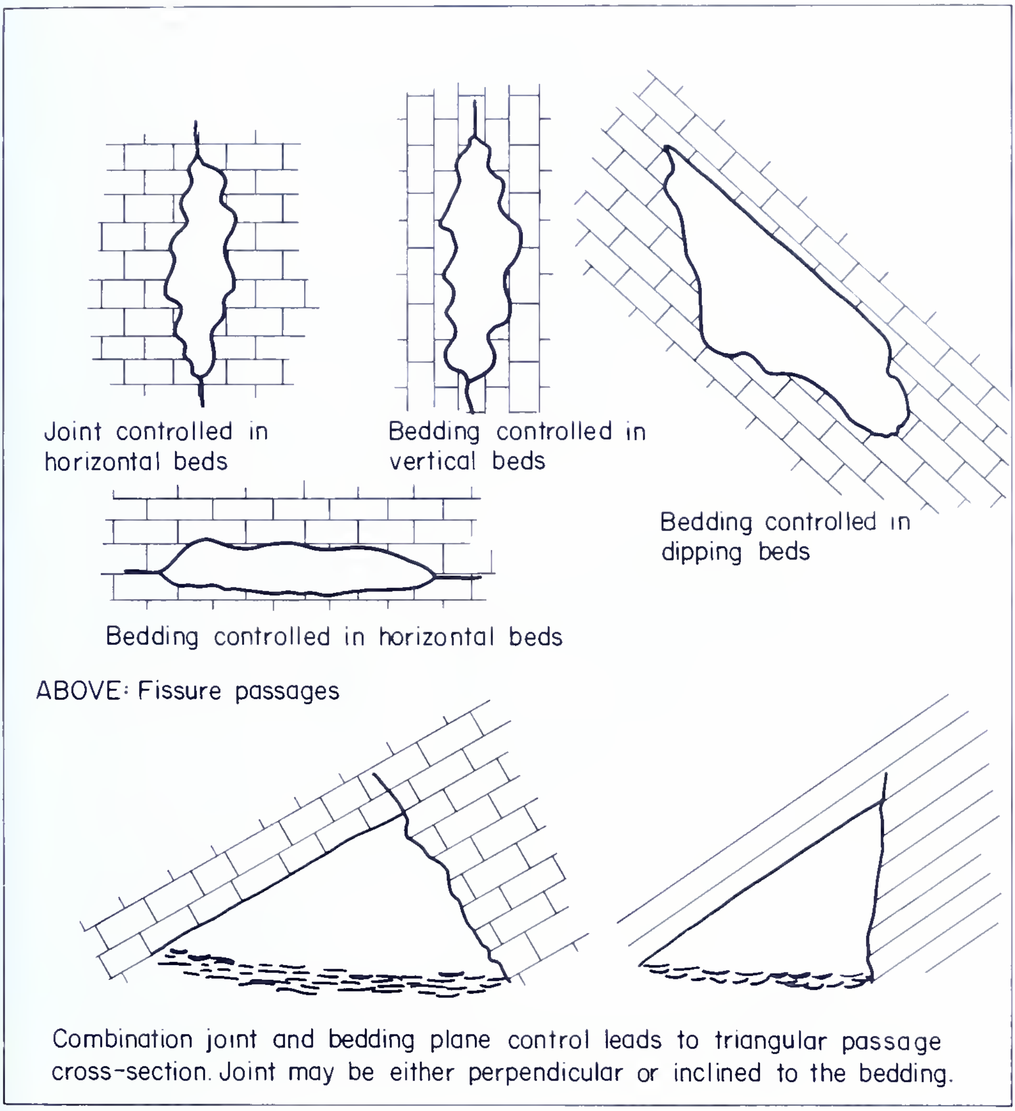

Joint controlled in horizontal beds
Bedding controlled in vertical beds
Bedding controlled in dipping beds
Bedding controlled in horizontal beds
ABOVE: Fissure passages
Combination joint and bedding plane control leads to triangular passage cross-section. Joint may be either perpendicular or inclined to the bedding.

Figure 8. Cross-sectional passage shapes which have been controlled mainly by the structure of the surrounding bedrock.

few shafts contain waterfalls but that is uncommon. The accumulated waters leave the bottom of the shaft through a very small complex drain passage usually of dimensions much less than the shaft itself.

Shafts form at the edge of a resistant caprock where a source of low pH water is available. The relationship to underlying cave passage may be fortuitous, or the drain from the shaft may be part of the cave drainage system. Sometimes shafts and horizontal passages suffer a near miss and the shaft is seen cutting out a slice from the cave wall, just as a giant auger might do.

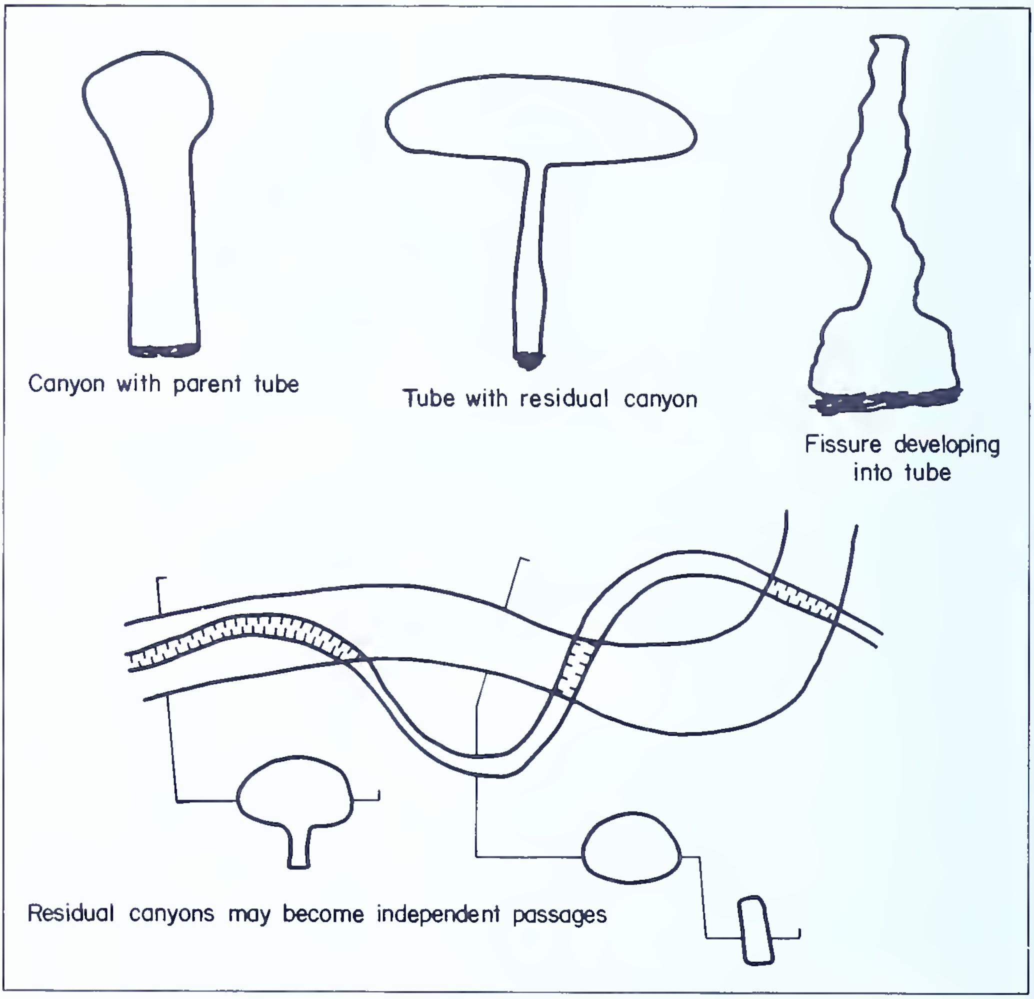

Canyon with parent tube
Tube with residual canyon
Fissure developing into tube
Residual canyons may become independent passages

Figure 9. Composite passage cross sections that form as a result of a combination of structurally controlled features.

Shafts are very common features in all the plateau karst regions of the Appalachians and they reach their maximum development in the southern end of the range in northern Alabama and Georgia where some shafts such as Fern Cave, Alabama, and Ellison Cave, Georgia, have depths of over 400 feet. In the Appalachian Plateaus, shale horizons serve as the resistant caprock.

Shafts are uncommon in Pennsylvania (although a few small examples can be found). This is partly due to lack of an appropriate caprock and partly due to lack of relief.

There is no well-defined term for other vertical solution openings, and here we use *chimney* in a general sense to include those vertical openings that do not have the diagnostic features of the vertical shafts. Chimneys are the common type of vertical opening in Pennsylvania caves and typically are solutionally widened joints or fissures, or solution passages extending along bedding planes in near-vertical limestone.

The deepest vertical opening in Pennsylvania, Big Ridge Cave in Mifflin County, is a sequence of chimneys along steeply-dipping beds cut in places by vertical joints across the bedding. A unique and interesting cave is Sunnyside Cave, Centre County, which is an alpine cave in miniature. The cave is predominantly vertical with intervening horizontal passages. Some of the vertical openings are chimneys following the bedding planes in the 80° dipping limestone. In some places, however, true vertical shafts are developed which begin to take the characteristic circular shape and have completely vertical walls that cut the steeply dipping bedrock.

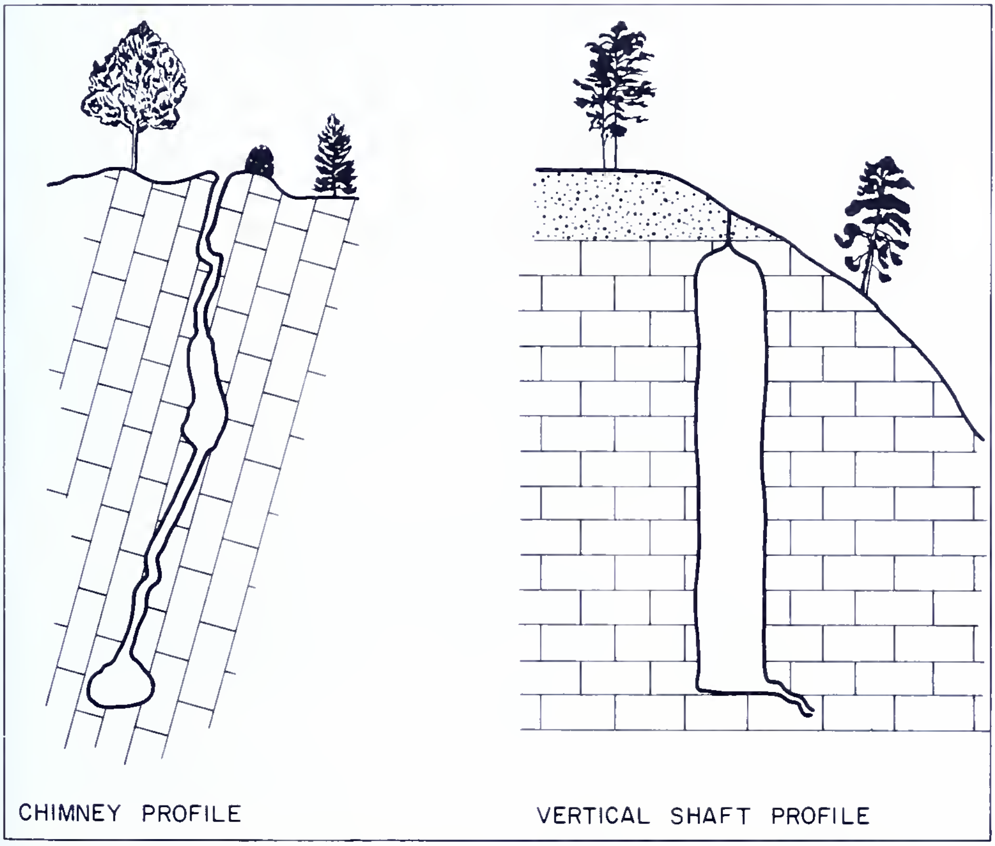


Figure 10. A comparison of chimney and vertical shaft profiles.

PASSAGE TERMINATIONS

If we accept the premise that caves form by moving groundwater, it follows that passages cannot have blind bedrock terminations. Only in the case of network patterns where water is circulating simultaneously through all joint openings could a few of these have blind ends. Caves, however, do have ends. The nature of these terminations is often of the greatest importance for the proper interpretation of the cave system.

Brucker (1966) very carefully pointed out that most of the big trunk conduits of the central Kentucky cave systems end in terminal breakdowns. The terminal breakdowns cut the once-continuous conduits into truncated passages. By careful examination of all available cave maps it is sometimes possible to reconstruct the conduit by the alignment in plan and in elevation of the truncated fragments of passage and by agreement in general passage cross section and morphology. Such analysis sometimes also predicts the existence of previously unknown passages if these are necessary to complete the pattern.

Pennsylvania caves are usually highly truncated since they occur under limestone valleys, at shallow depths, and without any protective caprock. Instead of miles of interlacing passages and tunnels, typical Pennsylvania caves have lengths of hundreds of feet. Often a single fragment is all that is accessible. Some are terminated by breakdowns, but many more terminate in clay chokes. The caves all contain layers of silt and clay on the floors, and in places these fill deposits reach the ceiling and effectively block the passage, although presumably it was open to groundwater flow at some earlier time.

Another effective termination of some Pennsylvania caves is the siphon (also referred to as a sump), which is a place where the passage ceiling dips below water level. Some siphons have been bypassed by diving, but that is a dangerous undertaking in small, cramped cave passages and a very limited amount of underwater exploration has been carried out in Pennsylvania.

ENTRANCES

To the explorer the entrance is the most important feature of the cave. Without it, the cave goes forever undiscovered. Entrances are found in many forms, in dolines, at the bottoms of chimneys and shafts, on hillsides where passages intersect the surface, as spring mouths, and in roadcuts and quarries. The common feature to almost all cave entrances is that they are the results of statistical accidents. Except for entrances in sinking streams and springs, the entrance is not an intrinsic part of the cavern development process. The cave forms without an entrance. The entrances are developed later as the downwasting of the landscape dissects and truncates the cave system. Entrances are closely related to the truncation processes that break up caves (Figure 11).

Curl (1958) examined the statistics of cave entrance distribution as a function of cave length and finds that the data of Pennsylvania and

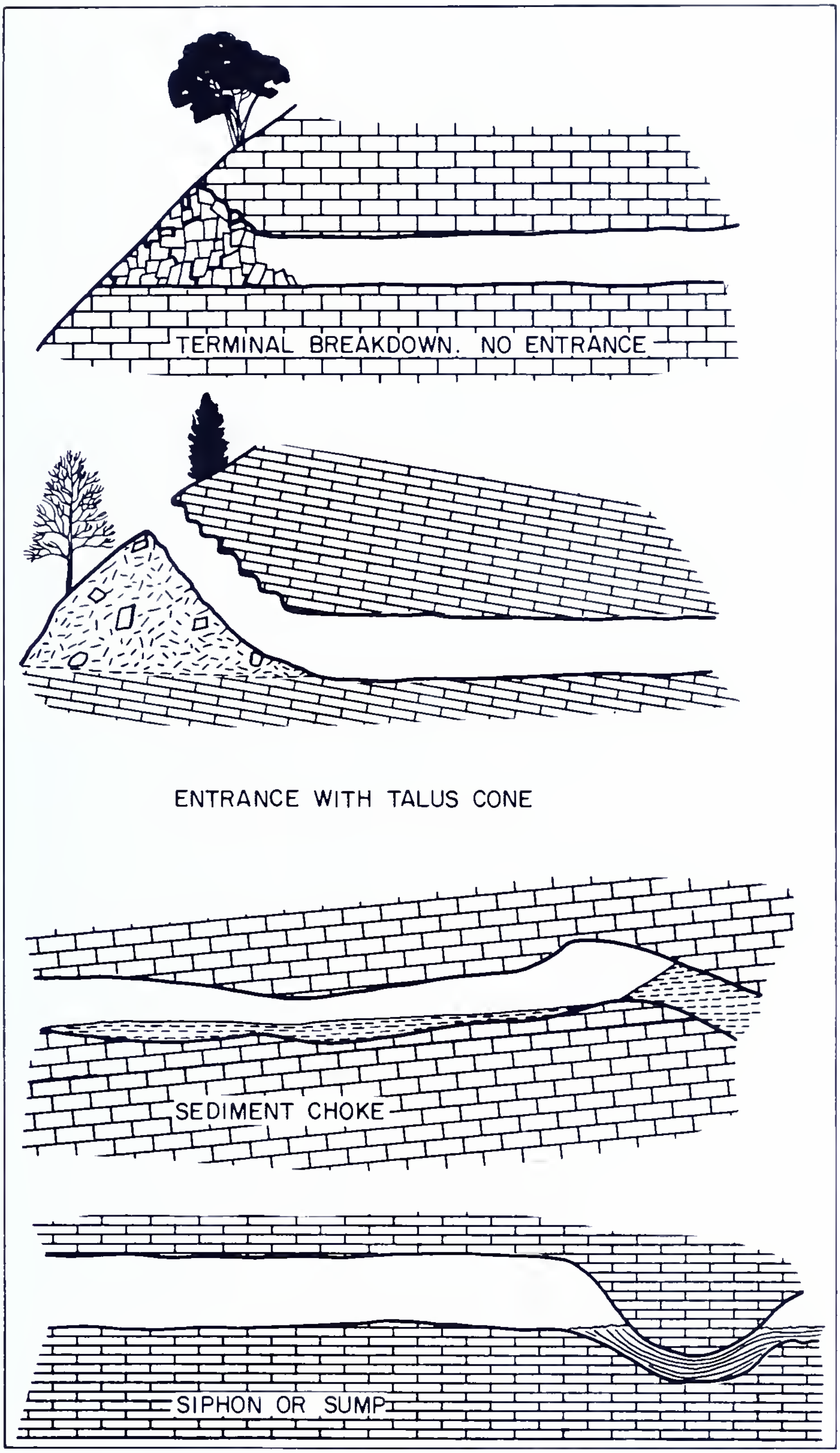


Figure 11. Several types of cave passage truncations.

West Virginia caves fit a Poisson distribution with the number of entrances increasing from an average of 1.13 for caves with lengths greater than 100 feet through 1.24 for caves longer than 500 feet to 1.33 for caves longer than 1000 feet. The theory predicts a very large population of caves with zero entrances. The general fit of this stochastic theory is in agreement with the theory that the formation of entrances is a random process rather than an intrinsic part of cavern genesis.

CAVE ROOMS

One common feature shown on most cave maps is the cave "room." Cave rooms are a very diverse class of features about which relatively little can be said. The usual "room" is a place in which the cave widens or heightens above the average passage through which the explorers have been traveling. Among the many diverse origins for rooms may be listed:

1. Intersections of several passages.
2. Places where breakdown has fallen while groundwater was actively circulating. This stopping process leads to some very large dome-shaped rooms.
3. "Rooms" consisting of a fragment of large conduit reached through a cave system consisting of much smaller conduits.
4. "Rooms" formed mainly by vertical solution and intersected by smaller horizontal passages. Various dome rooms formed by shafts or complexes of shafts are of this type.
5. Actual widenings of horizontal passages. Such irregularities in the shape of cave passages occur, but the causes are usually not known.

The cave room is much like the overall cave pattern itself. Any particular room is a feature unique to that particular cave and must be interpreted on the basis of local conditions.

SOLUTIONAL SCULPTURING

Most caves have a variety of small features of relief sculptured on the walls, ceilings, and floors (if the bedrock floors happen to be exposed). Many of these have been described and classified, mainly by Bretz (1942). Bretz separated these features into vadose forms and phreatic forms and used them as criteria for establishing certain caves as having a vadose or phreatic origin. It now seems that the interpretation of some of these features is less clear-cut than Bretz presumed, but the descriptions and nomenclature have been preserved.

Anastomoses Bedding plane and joint plane anastomoses are tiny networks of tubular openings occurring along bedding and joint planes.

They are of great complexity and differ from spongework in being nearly circular in cross section and actually resemble a miniature cavern system. They are usually seen only in cross section where slabs of rock have broken away along the plane of weakness. The openings are rarely large enough to crawl into. Ewers (1966) has examined anastomosing channels in Kentucky, and while agreeing with Bretz that they are of phreatic origin, argues that they form in conjunction with main cave passages.

Boxwork Boxwork is an intricate set of thin partitions resembling a honeycomb extending outward from the walls of a cave passage. Boxwork partitions are usually the remnants of thin-bedded clays that have infiltrated the limestone and thus were left behind by solution. Boxwork is also formed by differential solution of limestone containing secondarily deposited veins of calcite in joints and cracks. Sometimes calcite or quartz crystals are found in the clay layers. The classic boxwork of coarsely crystalline calcite is almost unique to the Black Hills Caves, South Dakota (White and Deike, 1962), but minor boxwork occurs in many caves.

Ceiling Channels Ceiling channels are what appear to be upside-down stream beds in the roofs of passages. According to Bretz, that is exactly what they are. If a passage were to be filled nearly to the ceiling with sand and clay, the vadose stream would be forced to flow on top of the fill and thus might well completely fill the passage. If the stream did not have a high gradient, its power of solution would be greater than its power of abrasion, and it would dissolve a course in the soluble ceiling faster than it could abrade a course in the insoluble floor. Later as the channel enlarges, flow would increase and the fill would be gradually removed, leaving a ceiling channel behind. Seawra Cave, Mifflin County, is Bretz's type locality for ceiling channels.

Clay Fins A feature sometimes observed in the Appalachian caves, not mentioned by Bretz, is the clay fin. Clay fins are similar to boxwork in that they are projecting layers of clay or shale left behind by the solution of the surrounding limestone. They differ in that the vertical partition joining the horizontals and closing the "box" are lacking. A two-stage development in the formation of the bedrock is necessary to explain the presence of the vertical partitions. The first stage involves the deposition of the limestone and its subsequent jointing. Then either clay is added from outside sources, or solution removes some of the interbedded clay and redeposits it in vertical joints. Presumably the clay inclusion hardens so that subsequent erosion of the enclosing limestone by phreatic waters leaves the fins intact.

Continuous Rock Spans Continuous rock spans occur in some cave chambers. If they are nearly horizontal, they are similar to natural bridges. If greatly inclined or vertical, they tend to be slabs or pillars. Bretz considered these a phreatic feature, although it is easy to show a vadose mechanism for some. The "Giant's Shield" in the historic Indian Caverns, Huntingdon County, is the type example.

Horizontal Wall Grooves Horizontal grooves in cave walls are formed by a cave stream cutting its way laterally into the wall, usually along a bedding plane. Sometimes it will leave the main passage completely and will be found flowing parallel to the main channel in a low-roofed passage extending some distance to one side.

Incised Meanders Incised meanders in cave walls occur when a small vadose stream is flowing in the clay fill of a large passage. The stream will meander back and forth and will sometimes cut both laterally and vertically into the rock wall of the passage. Thus, at the extremes of its meander loop, the stream will disappear into a conical trench in the wall, to reappear a few yards farther on. Occasionally, these meander loops become large enough to walk through, and one can leave the main passage and return to it by completing a half circle.

Joint-Determined Wall and Ceiling Cavities Joint-determined wall and ceiling cavities are deep, narrow slots extending along a joint, often for many feet. They tend to be wider at the intersection with the cavern passage and to narrow farther along the joint. This was considered evidence that they were formed by the phreatic water in the passage, and not water descending along the joint. However, more recent evidence indicates that ceiling cavities may well be due to solution by a mixing of water from the joint with water of a different chemistry in the main channel.

Pendants Pendants are vestiges of bedrock hanging below the ceiling or a flat-bottomed ledge. They usually occur in groups and grade laterally into smooth ceiling. They are believed to be the remnants of an older ceiling and to be formed by solution or abrasion of the ceiling during times when the vadose stream flooded the passage.

Potholes High gradient streambeds in caves are often eroded into complex forms of which circular basins called potholes are the most common. These vary in size from a few inches to many feet. Usually associated with the potholes are other etched and eroded pinnacles in the limestones very similar to forms found in surface stream beds. Ford (1965) discusses the mechanism of origin of these features from certain British caves.

Scallops Scallops are cuspate pockets that form on exposed bedrock surfaces by the differential dissolving action of moving water. A related form is the flute. Scallops are pocket-like. Flutes are asymmetric grooves which in ideal cases completely encircle the cave passage. Scallops form under either free-surface stream or pipefull passage conditions. In a few cases elliptical tube passages have been observed with a uniform scalloping on floor, walls, and ceiling.

Curl (1966, 1974) and Goodchild and Ford (1971) have made both theoretical and experimental studies of the mass transfer processes in flute formation. Scallops are more complex, and an analysis of scallop formation is in Curl's most recent (1974) paper.

Both flutes and scallops can be used to determine the direction of past water flow. The steep side of the asymmetric cusp is on the upstream side and the more gentle slope is on the downstream side (Figure 12).

Spongework Spongework is a highly complicated system of tiny holes and interconnected cavities found on cave walls. It gives the wall a very definite swiss cheese effect. The most reasonable theory for its origin is the differential solution of limestone by the etching action of nearly stagnant water. This great complex of holes within holes may extend many feet into the wall, and it is very difficult to see how it could have been made by flowing water, or even preserved in the presence of it. Spongework is not common in caves, although Carlsbad Caverns, New Mexico, and Wind Cave, South Dakota, have extensive areas of it. Spongework can enlarge to become a cave itself with the pattern of the spongework maze.

Wall and Ceiling Pockets Wall and ceiling pockets are larger than spongework cavities and are usually separated by stretches of unaffected rock. They resemble kettleholes and are usually circular or elliptical in outline. They may be deeper than they are wide and have smooth sides with no indication of the reason for such deep penetration. They are explained by Bretz as being the result of differential solution of pockets of less resistant rock. It is difficult to explain what lithologic variations in the limestone would differentially weather to give the smooth kettle-shaped outlines. The concept of *mischungskorrosion* explained in a later section provides a better explanation for both these features and the joint-controlled cavities.

OVERALL CAVE MORPHOLOGY

A cave, as the term is used in this publication and indeed in most writings on caves, has a strictly anthropomorphic definition. A cave is that sequence of entrance, passages, and rooms that can be traversed continuously by a human explorer. Thus, a single long conduit that has been broken by entrenchment of a minor surface valley so that the entrances to the two fragments are 100 feet apart, is considered to be two caves. On the other hand, two parallel conduits, on different levels, related to different drainage lines but which happen to be fortuitously

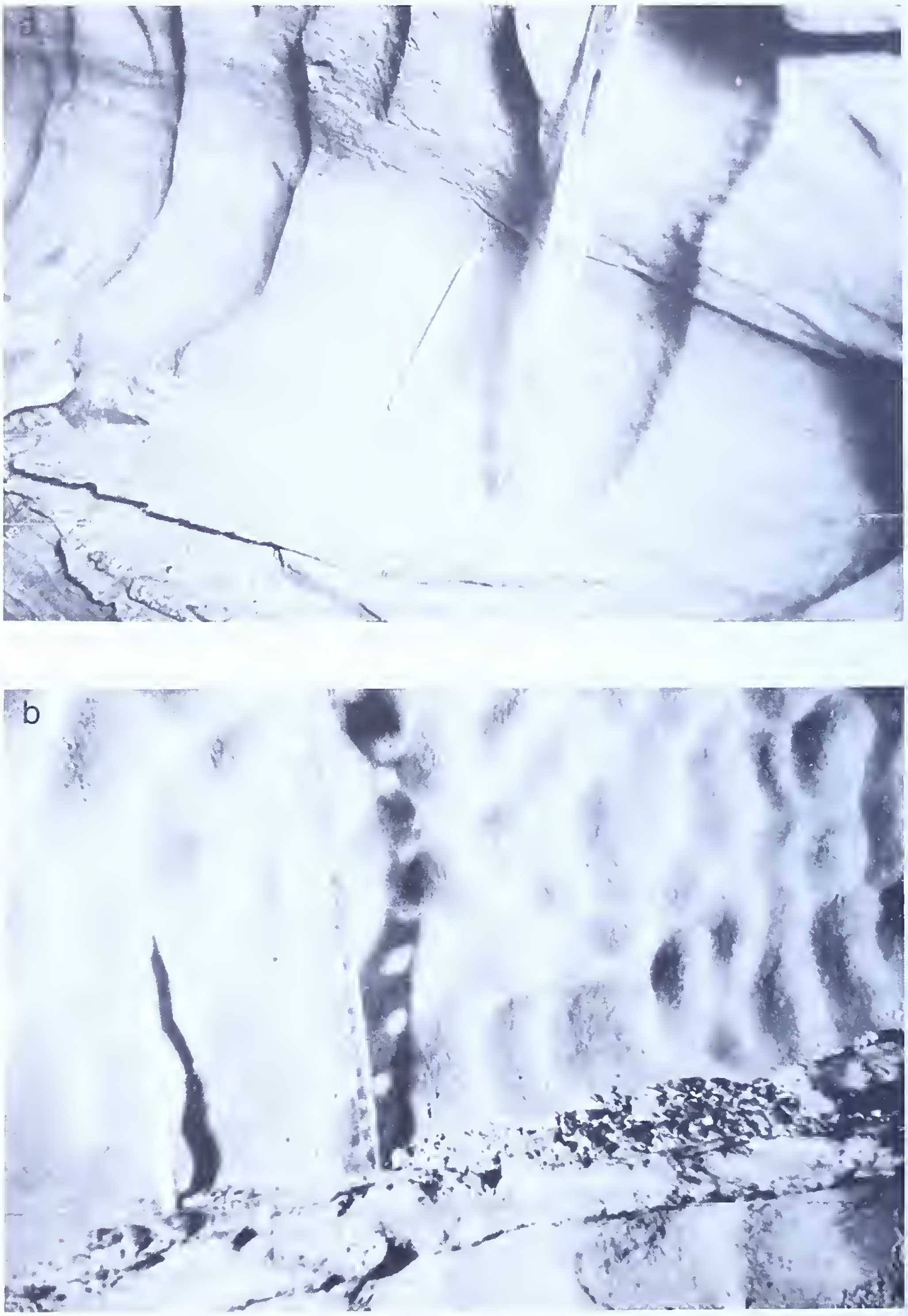


Figure 12. Solutional scallops from Milroy Cave, Mifflin County.
a. Flute-like scallops from water at moderate flow velocities.
b. Irregular scallops from higher flow velocities.
Photos courtesy of A. Ogden.

connected by hundreds of feet of painful crawlway, are considered parts of the same cave.

If we are to have a scientific understanding of caves and cave processes it is necessary to regard real caves as assemblages of passages that may have different histories, and to try to interpret the way in which these passages are assembled and truncated to form the final cave as it is now observed.

The overall pattern of the cave can be classified in terms of the number of individual drainage lines present, and according to the geometry of the passages. We may call a cave pattern *simple* if it contains only one drainage line and *complex* if it contains more than one. Simple patterns would include fragments of single conduits and would also include network caves. In spite of the network cave having a large number of individual passages, the evidence points to the flow having moved along all of these simultaneously and so it is in effect a single drainage line much in the way that a braided river is still considered a single stream. Most Pennsylvania caves are small and are simple caves.

Complex systems seem to fit into three basic categories, although there are no sharp lines of demarcation between them. These are

(i) Networks
(ii) Conduit Systems
(iii) Branchwork Systems

Network systems are simply large network caves. The key feature is the multiconnecting passage arrangement. Conduit systems are those that have interconnecting channels on a larger scale than the networks, certainly with a wider spacing than the regional joint system. Some parts of the conduit system may represent the drainage line that was used during the earlier history of the cave and is now abandoned. Other passages may be cut-around routes, spill-over routes, piracy routes to lower levels and the like. A conduit system, in essence, is what would be expected from a surface stream if all the previous history of the valley were somehow preserved as downcutting took place. Branchwork systems are those in which a well defined tributary system can be established. This means that several feeder conduits must be active at the same time.

From the above it is clear why such classification schemes can only be applied to moderate-sized cave systems. If we consider entire drainage basins and were able to reconstruct all cave passages that at one time or another played some role in the movement of groundwater through the basin we would probably find all the categories represented somewhere in the drainage net. The conduit systems might be in the downstream portions near the spring discharge point and the branchworks upstream in the headwaters. Networks are often included with more complex cave patterns.

If cave passages do, in fact, represent underground drainage systems, then the degree of interconnectivity, branching and similar parameters would likely follow some sort of statistical laws analogous to Horton's Laws, which describe surface stream systems. Parameters analogous to stream order, branching ratio, and the like could be sought.

Curl (1960, 1966) has studied distribution of cave lengths and number of cave entrances for various populations of caves. Cave lengths follow a Poisson distribution due to the random nature of the truncating mechanisms (analogously to the random distribution of entrance formation and entrance closure). These calculations also yield a parameter that Curl (1966) calls the "karst constant," which seems to be a characteristic of particular cave populations. It seems clear that much more can be done with the geometry of cave system morphology.

CLASSICAL THEORIES OF THE ORIGIN OF CAVES

The processes that lead to the development of caves have been the subject of discussion and dispute for hundreds of years. We can date the beginnings of a modern geological understanding from about the late 18th or early 19th centuries when it gradually became accepted that caves form in limestone because of the solubility of the bedrock in slightly acidic groundwater. Thinking on this subject has followed parallel—but nearly independent—paths in Europe and the United States. The literature is vast and the outline that follows touches only lightly on the major contributors.

Until quite recently most writings presented only physiographic arguments. Central questions concerned the existence or nonexistence of a karst water table, the location of cavern development with respect to that water table, and the depth of groundwater flow below the water table. These writings have much in common and are discussed as the "classical" theories of cave origin. Each theory bears the strong stamp of one investigator's personality and it is quite meaningful to speak of "Swinnerton's theory" or "Malott's theory." In more recent years attention has turned from arguments about the water table and its influence on cavern development to a more fruitful investigation of the physics and chemistry of the movement of groundwater in karst. Here the central questions concern the chemical equilibria between groundwater and limestone rocks, the kinetics of these reactions, the hydraulics of groundwater flow in a karsted carbonate aquifer, and the influence of specific structural, stratigraphic, and lithologic parameters as boundary conditions for groundwater flow. Unlike the classical theories, the hydrological treatment of cave origin is the product of many contributions that fit into an integrated picture. There is no one dominant investigator.

Classical theory separates into three main classes: those that propose cavern development deep below the karst water table; those that propose cave formation by laterally moving water near the top of the phreatic zone or in the floodwater zone; those that propose development by free-surface streams much as an underground analogy to surface streams.

DEEP PHREATIC THEORIES

In Europe, cave formation deep below the water table was first proposed by Cvijic (1893). By arguing that the groundwater in karst circulated at depth through many bedding planes, joints, and fissures much in the manner of groundwater circulation in other porous rocks, Cvijic arrived at a class of "groundwater caves" that were formed when the bedrock was removed by solution. Grund (1903) arrived at much the same conclusion. Both of these writers, however, were interested more in the hydrology of the karst than in cavern development and so did not carry out much in the way of deductions about the expected patterns, profiles, cross sections, and general morphology of the groundwater caves. It was, however, this same basic idea that Davis used for his much more elaborate treatment of the development of caves in the deep phreatic zone.

The deep phreatic theory is also called the "two cycle theory" in much of the literature. It was proposed by Davis (1930) and later expanded by Bretz (1942). The Davis paper was the first in United States literature to really examine the problem of cave origin in a systematic fashion.

According to Davis, solution takes place in the phreatic zone during the old age stage of the geomorphic cycle. Upon reaching the water table, groundwater continues toward its outlet along flow lines that curve deeply into the phreatic zone. Solution takes place uniformly along all these possible paths. The force driving this flow is the hydrostatic head between base level and the highest part of the water table in the interior of the interstream areas. As the geomorphic cycle progresses, the water table gradient becomes less, the hydrostatic head decreases, and solution becomes less. Davis apparently believed that very little enlargement took place in the vadose zone.

When rejuvenation takes place, usually in the form of regional uplift, the rejuvenated streams downcut into the old valley floor. The water table is lowered and gradually the upper levels of the cavern system become air-filled. At this stage dripstone deposits begin to form in the passages, due to vadose water carrying in minerals from the upper beds of the limestone. Thus, Davis provided a mechanism for separation of solution and deposition into two stages in the cavern cycle.

Davis was greatly handicapped in making his study by the almost total lack of any quantitative data on caves. He carefully located every available paper and map and found most of these to be inadequate. His argument is based almost entirely on the ground plan of cave systems. The following points are listed as highly critical:

1. Formation of closed loops in passages. Maze-type caves are an extreme example of this.
2. Passages that branch in *downstream* direction.
3. If vadose streams developed cavern systems in an analogous manner to the development of valleys by surface streams, we should see a dendritic pattern in the cave ground plan. This is not observed.
4. In numerous instances we find large galleries connected by small passages. This could not have been done by a vadose stream.
5. Longitudinal profiles of many cavern passages reveal many ups and downs in the floor and ceiling levels. This is not at all consistent with a vadose stream.

From consideration of the above and other points Davis reached the conclusion that abrasion plays only a very small part in the origin of a large cavern system. Origin by vadose streams acting solutionally is very doubtful but cannot be completely ruled out by Davis' theory.

There is an especially awkward problem associated with deep phreatic theories. It was recognized by Davis but was not solved. If one examines the diagram for deep phreatic flow (Figure 13), it will be seen that the type of cave that should form is one with sloping or stair-step levels interconnected at frequent intervals by irregular pits to still lower levels.

The total vertical relief of the cave should be equivalent to the total depth of circulation of groundwater. This would be expected to be many hundreds of feet. And yet few caves are observed to have this pattern.

The Davis two-cycle theory can be summarized as follows:

Stage I	Formation of all cavern passages by deep circulation of groundwater in the phreatic zone. Cave formation takes place during the old age stage of geomorphic cycle, stops during peneplain stage, and awaits uplift.
Stage II	Cavern system is lifted above water table and becomes air-filled. At this time dripstone deposits form, breakdown takes place, and cave begins to age.

J Harlan Bretz (1942) was the next to defend the deep phreatic theory. He first carefully examined 100 caves for evidence of vadose

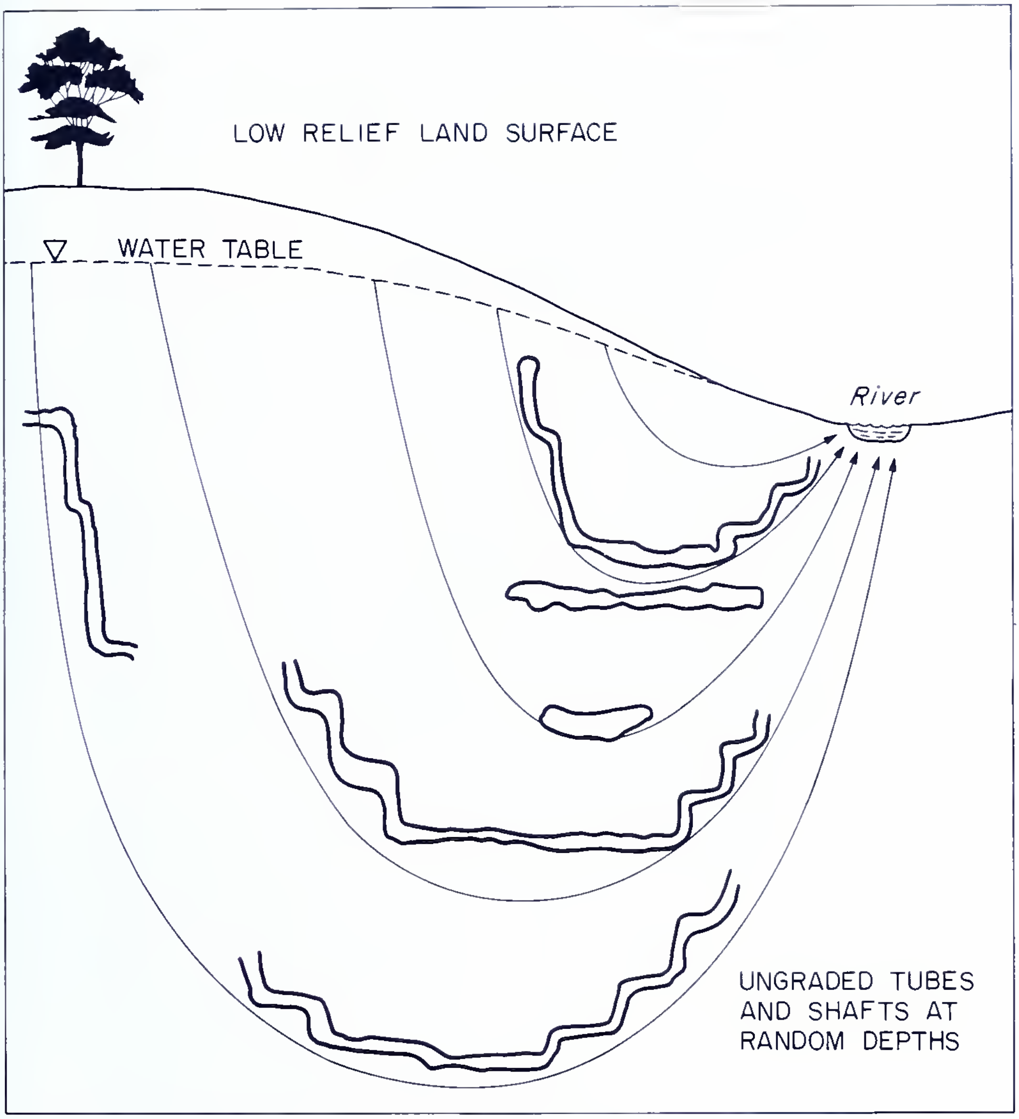


Figure 13. Theoretical cave patterns resulting from deep phreatic flow.

and phreatic action as evidenced by various solution features. His conclusions were that nearly all caves examined were of phreatic origin. Vadose features when present were later modifications due to present-day streams invading the already formed cavern. He also introduced an epoch of clay filling to take place at the close of the first stage of cavern development. All caves are believed to have undergone the fill epoch. As evidence of this, Bretz sites instances of clay trapped in niches high above present cave floors.

Caves existing today are misfits. They have no general relationship either to the streams they may contain or to the topography above. Bretz proposed, as did Davis, that caves in the vadose zone are remnants of a previous erosion cycle and formed before the land above them was peneplained. It is only during the dying stages of an erosion cycle that caverns are formed. During the peneplain stage, the epoch of clay filling takes place. Upon rejuvenation of the land surface, the caves are drained and vadose streams begin to remove the clay fill. In these caves vadose and phreatic features become superimposed.

The Bretz modification of the deep phreatic theory is

Stage I	Same as Davis. Deep-seated solution by groundwater circulation beneath an old age land surface.
Stage II	Fill Epoch. Caverns lying beneath a peneplain are saturated with stagnant water. Fine clay and silt, filtering down from the land surface above, fills the cavern completely (or nearly so) with unctuous clays.
Stage III	Cavern system is drained of water. Invading vadose streams begin to remove clay fills. Sometimes this may be done completely until the vadose stream is running on bedrock floors. In other cases most of the cave is still clogged with clay. Vadose features are superimposed on the phreatic record. Some enlargement may take place by the formation of floor slots and meander niches.

SHALLOW PHREATIC THEORIES

Theories of cave origin from groundwater moving near the surface of the water table have several variants. Swinnerton and his followers place the main level of development in the floodwater zone where the water table fluctuates with the seasons. Lehmann and other European writers, concerned with caves in high relief terrains, speak of pressure tube flow active only during the spring floods. More recent theorizing, also following Swinnerton, has placed the zone of cavern development just below the water table rather than in the floodwater zone.

Swinnerton (1932) claimed that the deep paths of flow reported by Davis were true only for porous media. Limestone is much different and one would obtain different flow paths. Once groundwater reached the water table, it would flow in a zone at the top of the table. Deep circulation would be negligible. Note that Swinnerton is more extreme than later shallow phreatic theorists in that he believes major flow takes place in the floodwater zone at the very top of the water table. The main points of Swinnerton's theory may be summarized as follows:

1. Cavern enlargement takes place by means of lateral flow of groundwater. Lateral flow begins *after* entrenching of surface streams has begun. This would mean that present day caves near the water table are related to the present erosion cycle.
2. The lateral enlargement of the cave is similar to the headward cutting of a surface valley.

3. Piracy should occur between levels and between caves on the same level.
4. Major cave solution begins to occur just as soon as the downcutting surface streams provide sufficient hydrostatic head. Thus, the cave origin begins in the youthful stage of the•erosion cycle.
5. The underground drainage will become well integrated only when surface topography is reaching a mature stage. In maturity, there is a maximum relief and therefore maximum gradient to the water table, and a high hydrostatic head. Cutting of the cave system would be expected to take place at its maximum rate during this stage.
6. During maturity the erosion of the cave system is faster than the erosion of the surface. This is particularly true, since much of the drainage will be diverted underground during this stage and surface erosion correspondingly retarded. Thus, the water table will reach an old age or peneplain stage long before the surface does. In the old age stage there is little hydrostatic head, and consequently little cutting takes place (Figure 14).
7. Swinnerton places great emphasis on crystal caves and points out that the lining of a cave with dogtooth spar will take place under the static water conditions to be found in these later stages.
8. During the old age stage, cutting still takes place in the floodwater zone in certain seasons due to torrential rains raising the

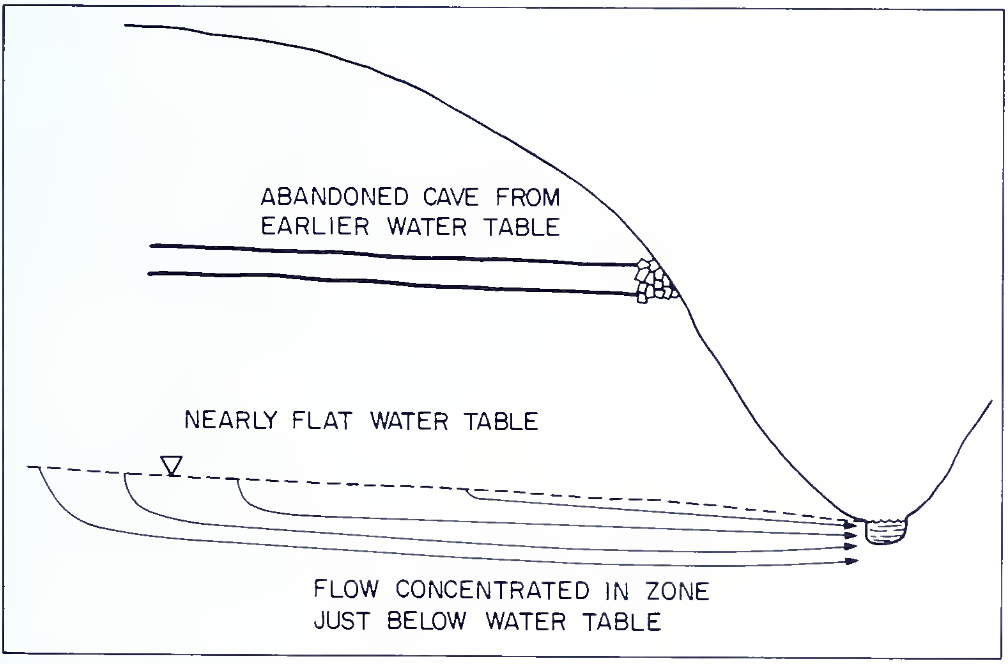

ABANDONED CAVE FROM EARLIER WATER TABLE
NEARLY FLAT WATER TABLE
FLOW CONCENTRATED IN ZONE JUST BELOW WATER TABLE

Figure 14. Theoretical cave development resulting from shallow phreatic flow.

water table and giving it a hydrostatic head for a short time. He points to Echo River in Mammoth Cave, which is known to rise 50 feet or more during flood season. By this theory, Mammoth is still being formed in its lowermost levels by spring floods.

9. This is strictly a one-cycle theory. As the surface valley downcuts, new levels are opened up and the floodwater stream pirates into them. Thus the vertical relief is constantly increased as the relief of the surface increases. It is only during the old age stage that breakdown and wearing away of the overburden would begin to remove the cave. Deposition of dripstone occurs in the upper levels concurrently with the removal of limestone from the lower levels.

It is important to note the relative position in the geomorphic cycle of the Davis and the Swinnerton theory. According to Davis, caves are related to the old age stage of an earlier cycle. According to Swinnerton, they would be related to youth and maturity stages of the present one.

The variation of the shallow phreatic theory proposed by Lehmann (1932) was designed to cope with the situation in very high relief limestone massifs much as the Alps and the Pyrenees. Lehmann proposed that caves form by "pressure tube" flow in systems of pipes and conduits that have no relation to the regional water table and indeed that a water table as such does not exist in an alpine karst. The concentrated flows of water that are supposed to form the caves are not vadose streams, since they are not required to be graded. These pipes may have deep curved loops and carry water to considerable depths below their point of discharge. Flow is envisioned to be rapid and in a turbulent regime. Lehmann was one of the first to apply the newly developing science of fluid mechanics to groundwater flow problems and presented a number of formulae for the flow velocity as a function of hydrostatic head. The conduits may cross over one another and full pipes may lie at higher levels than air-filled conduits. Flows depend only on the relative rates of recharge and discharge.

VADOSE THEORIES

Various theories that propose cave formation by the simple action of free-air-surface underground streams (Figure 15) are much more difficult to characterize, because there are many of them and not all use the same conceptual basis. In the list that follows we have attempted to outline the principal American contributions and just hint at some of the European ones.

One of the first reactions to Cvijic and Grund was the treatise by Von Knebel (1906) which discussed in detail the underground water courses of several karst systems in Germany and eastern Europe. In

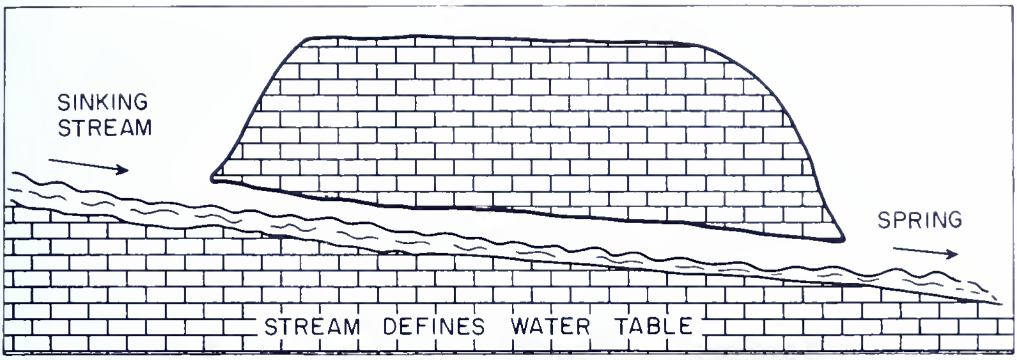


Figure 15. Theoretical cave formation according to the vadose theory.

these cases, fragments of the underground streams could be clearly seen and the effects of annual floods were likewise clearly visible. Dye tests were used to demonstrate that these fast-running streams still required quite a finite time to transmit water but that the dye was not diluted and thus the karst stream did not become part of the "groundwater" beyond the terminal siphons in the channels. A similar position was taken by Martel (1921) whose decades of exploration in French caves and others in western Europe had clearly shown him that underground rivers existed and that they were capable of mechanical as well as solutional transport of material. It has been vogue in much English-language literature to downgrade Martel. There is no doubt that Martel overstated his case, particularly with respect to the violence of the underground waters and with respect to his ideas on their sources and discharge points. However, at the time Martel wrote, there were probably few men alive who had such a vast personal experience of direct observation as he had. Further, Martel's observations were made principally in the high relief alpine karsts of France. That the concepts could not be taken directly to karsts in the Interior Lowlands of the United States is hardly surprising. The imprint of the authority of Martel on French speleology has been about as strong as that of Davis on American research. In each case there have been difficulties on the part of later researchers to unload themselves of the weight of these massive authorities.

Much of the cave descriptive literature written in the United States between 1900 and 1920 invokes some sort of vadose origin for caves. Papers by Matson (1909) and Green (1908) are typical. Few of these papers imply any definite sequence of geomorphic events or suggest any criteria for relating cave development to regional geology. In this sense it is difficult to consider them *theories* in the usual sense of the word. The theoretical treatments that appeared after the 1930 Davis paper are more detailed and three are outlined here.

Theory of Piper Piper (1932) was the first writer after Davis to propose a pure vadose theory. He was apparently familiar with Davis' essay but did not believe his principles were valid. Piper draws an analogy between the advance of an erosion cycle on the surface and the advance of the cycle underground.

Depending on the tightness of the joints, i.e. the permeability of the limestone, the underground cycle may precede or lag behind the surface one. In an area of loose joints, drainage may be captured so rapidly that a mature underground system is developed before the surface one gets a chance to develop. Inversely, if joints are tight, surface erosion may bisect the system before an integrated underground drainage net is developed.

The stages of development of an underground drainage system by groundwater in the vadose zone are as follows:

Youth - small channels advance headward from valley into the limestone. As passages continue to advance they will split into numerous branches. Some of these branches will intersect to form looped passages without main trunk channels.

Maturity - large amounts of surface water are discharging into the system. Trunk channels are established and these grow rapidly to become the main conduits of the cavern. Underground streams reach a sort of base-level, with tributary branches still downcutting toward this level.

Old age - in old age stage, an underground peneplain is established with lateral widening of the system as far as structure and stratigraphy will allow. Collapse sinks become common. The cavern system is bisected as surface old age and underground old age merge together with ultimate reduction of the entire land surface.

In Piper's theory, all the cutting action is attributed to the solution action of free-surface vadose streams. No credit is given to phreatic solution. No attempt was made to examine the caves involved in detail to see if the fine points would bear out the theory.

Theory of Gardner Gardner (1935) introduces his paper by stating that his theory will hold only for gently dipping, thick-bedded limestone. Only under these conditions will large caverns form. Both solution and abrasion play an important part in the formation of a large cavern.

1. Caverns are formed by tapping zones of static water in certain favorable beds by the downcutting of surface streams. Vadose water flows down-dip along bedding planes in permeable strata. Thus, the cave will always be on the up-dip side of the major surface drainage.
2. As downcutting continues, more levels develop and piracy takes place from level to level.

3. Surface waters are drawn into the cavern system. Once subterranean streams have been developed, the ratio of solution to abrasion is about what it would be for a surface stream.

Gardner makes an important point of the down-dip movement of vadose water: "When strata decline at a low angle, the long dimension of limestone caverns, when viewed from a horizontal plane, is ordinarily in the direction of dip; this fact indicates that for one reason or another water which dissolved the limestone followed the general direction of the dip of the strata to produce the cavern." He defends his theory by pointing out that he has never found records of drill holes intersecting large cavities beneath the surface below the water table. The regional dip required for his theory may be very slight. He quotes 50 feet per mile in the vicinity of Mammoth Cave. The reason that large limestone caverns are so rare is that a very unusual lithology of the strata is required in order for the tapping of vadose water to be effective.

Theory of Malott Malott's (1937) studies were limited to the karst region of southern Indiana. His theory can be best explained by simply quoting a section of his published abstract.

"Primitive, ill developed, and somewhat selective three-dimensional passageways are developed in limestone regions below the water table. Vadose waters under a flow-head develop underground flow routes from selected parts of the earlier prepared primitive systems. Fairly large streams are diverted from their surface courses into these underground routes. The diverted waters carve out and fully integrate the large caverns at or near the water table. The fully developed caverns bear unmistakable evidence of streams that coursed through them, though when long vacated, they tend to fill with dripstone, become encumbered with fallen rock, and lose parts of their stream-carved floors, as is well illustrated by upper galleries of some large cavern systems."

Malott placed a major emphasis on storm waters flooding into a cave and scouring it into a large size. Most of his work was done on the Lost River of Indiana, where indeed a large stream has used an underground route. More detail on the invasion theory may be obtained from two papers published much later, Malott (1949, 1951).

HYDROLOGIC MODELS FOR CAVE ORIGIN

Perhaps the most significant new concept since the classical papers on cave origin were written is that of relating cave development to groundwater motion and the overall hydrology of the drainage basin. The classical theories do indeed propose the formation of caves by circulating groundwater. However, the sources of this water are poorly specified, the rate of flow is never quantitatively described, and the influence of the structural, stratigraphic, and topographic setting is seldom taken into account. There has also been confusion between the theory of cave origin as a generalized process and the historic sequence of events at any one cave.

Caves can be best understood in the context of groundwater movement in a drainage basin. The entire watershed including all water sources and exits and the hydrogeology of the water-bearing rocks must be made part of the system. The caves themselves are fragments. They are segments of pipe that once carried water from some source to some exit. Usually the observable length of cave is only a tiny fraction of the total length of the drainage line. For this reason, interpretation is likely to contain a goodly element of conjecture. Correct conjecture is oft-times rewarded with a prediction of where to discover a new cave.

THE KARST DRAINAGE BASIN

Drainage basins in most limestone terrains are not exclusively underlain by limestone. If we consider the watershed for some major creek flowing from a carbonate area, we find in the Appalachian valleys the situation sketched in Figure 16. The Appalachian valleys are typically anticlinal with the older Ordovician limestones exposed on the crests of breached anticlines. The valleys are bounded by mountains supported by younger clastic rocks (typically the Silurian Tuscarora sandstone and the Oswego sandstone). Usually less than half the area of the drainage basin lies on carbonate rocks. Rainfall onto the clastic portion of the basin runs off quickly down the steep mountain slopes and aggregates into many small streams which flow in small side-valleys cut into the mountains (allogenic recharge). When these streams reach the limestone contact they sink in small pocket-valley swallow holes. Since the Appalachian valleys are usually elongate, the stream flowing into the end of the valley is often of considerable size and if it too sinks (which does not always happen in the Appalachians), it creates an even larger localized source of recharge.

Precipitation on the limestone valley floor also becomes part of the karst groundwater system. If there is no surface stream in the valley floor, all runoff enters the aquifer, often through sinkholes. If there is some surface drainage, the precipitation will be proportioned between surface runoff into the streams and internal runoff into the sinkholes.

Water leaves the basin through a water gap. The major stream typically heads in a large limestone spring near the limestone contact or tributaries fed by springs. There must be a drainage divide, often uncertain on the surface and even less certain underground, which separates the drainage basins of the various big springs. These under-

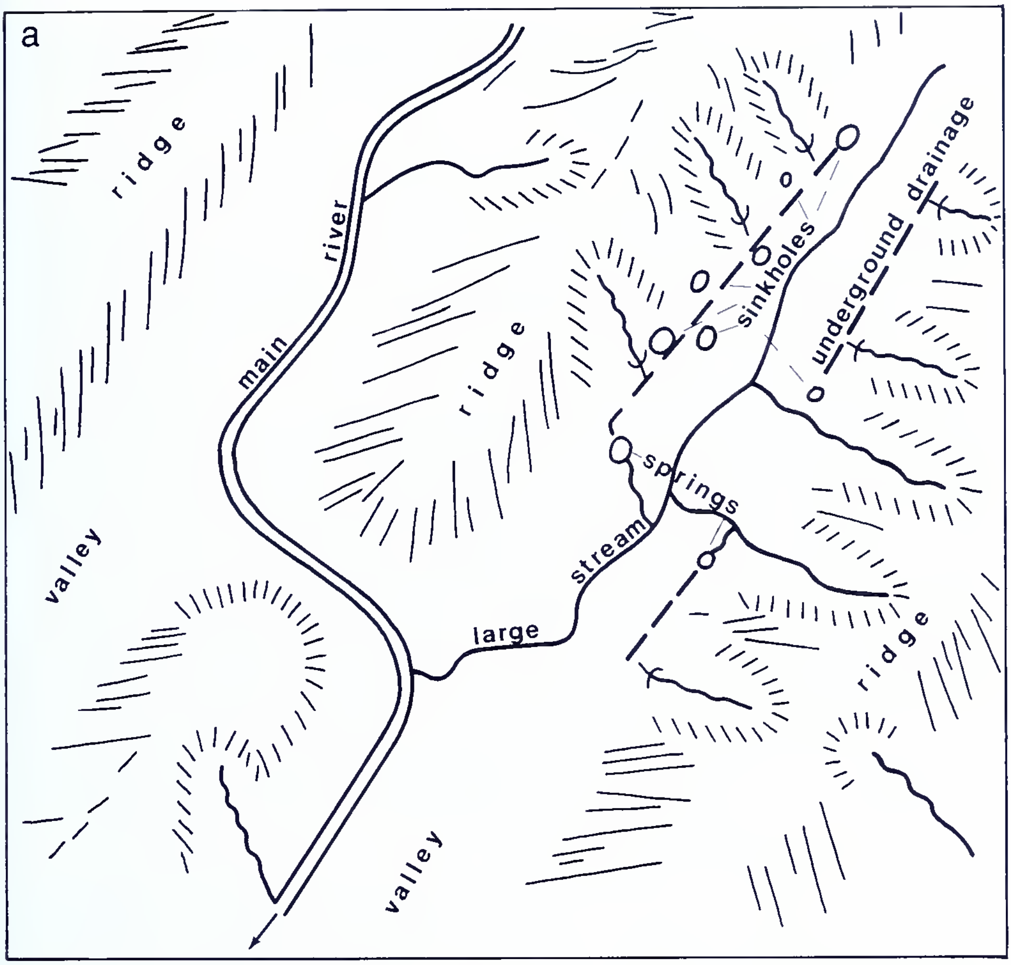
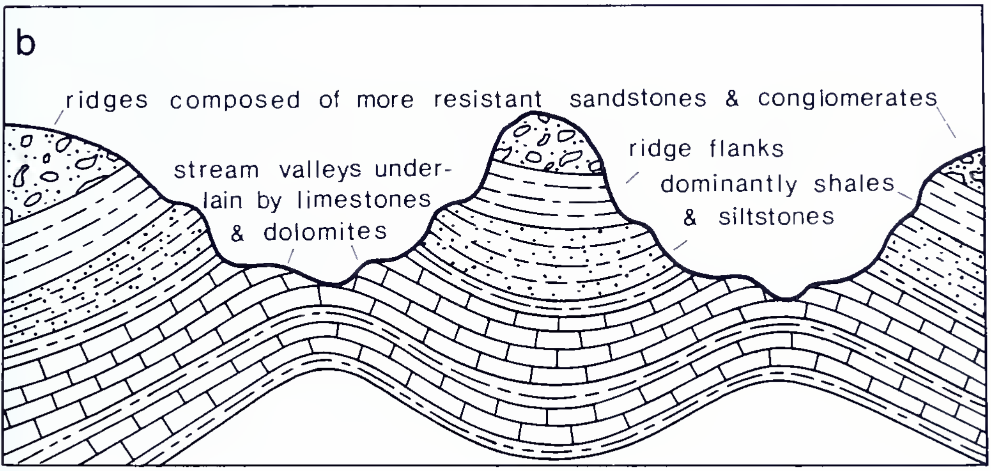


Figure 16. a. Typical Appalachian valley catchment area containing sinkholes, springs and streams.
b. Idealized cross section of Valley and Ridge geology with more resistant rocks forming ridges and valleys floored by carbonate rocks.


b
ridges composed of more resistant sandstones & conglomerates
stream valleys underlain by limestones & dolomites
ridge flanks
dominantly shales & siltstones

ground divides may change location with season of the year and make both quantitative measurement of water balance and water resource planning exceptionally difficult.

Karst springs in Pennsylvania vary greatly in size from small seeps to discharges large enough to form the headwaters of major streams. Penn's Creek heads in Penn's Cave in Centre County. The discharge varies from a few cubic feet per second (cfs) at low flow to more than 200 cfs during spring high flows. Mammoth Spring which forms the headwaters of Honey Creek in Mifflin County is of similar size.

Chemical studies of the carbonate springs of central Pennsylvania show two kinds of behavior (Shuster and White, 1971, 1972). Some springs, termed *diffuse flow* springs show little variation in their chemical properties throughout the year. Temperature and hardness remain constant regardless of the changing season, amount of precipitation, and the rate of discharge. Other springs, termed *conduit flow* springs, are very variable. Temperatures and amount of dissolved calcium carbonate vary with the time of year and with the amount of discharge. These springs are very responsive to storms such as summer thunderstorms. Evidence such as the presence of caves, sinkholes, and other karst features indicates that the conduit springs are the discharge points of cave systems, while the diffuse flow springs are discharging a groundwater that is moving more slowly through fractures, joints, and other smaller openings.

The karst basins in Pennsylvania therefore contain the following elements: a source of allogenic recharge that varies with the fraction of the basin area underlain by noncarbonate rocks; a surface drainage system on the carbonate rocks that may be partly or wholly pirated into the subsurface; and a network of underground conduits carrying water from sinkhole areas and from sinking streams to the big karst springs by direct routes. Existing with the underground conduit system is a body of groundwater circulating in the smaller openings of the carbonate rock.

CHEMISTRY OF LIMESTONE SOLUTION

Calcium carbonate is only slightly soluble in pure water. The solubility of $CaCO_3$ increases rapidly as the carbon dioxide (CO_2) content of the water increases. Carbon dioxide dissolves in water and then reacts to form carbonic acid which in turn reacts with calcite to form the more soluble bicarbonate. The equilibrium state of the system is controlled mainly by the temperature and the partial pressure of CO_2. All parameters are interconnected and are described by the reactions below. All reactions must be simultaneously at equilibrium if the system as a whole is at equilibrium.

(1) CO_2 (gas) $\rightleftharpoons$ CO_2 (aqueous)
(2) CO_2 (aqueous) + $H_2O \rightleftharpoons H_2CO_3$
(3) $H_2CO_3 \rightleftharpoons HCO_3^- + H^+$
(4) $HCO_3^- \rightleftharpoons CO_3^{--} + H^+$
(5) $CaCO_3 + H^+ \rightleftharpoons Ca^{++} + HCO_3^-$
(6) $CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{--}$

We will limit our discussion to calcite solution. Most carbonate areas also contain some dolomite and a similar set of reactions can be written for dolomite.

The chemistry of groundwater in carbonate rocks had become a highly developed subject in the early 1970's. Values for the equilibrium constants for the reactions and a discussion of the application to the thermochemistry to groundwater systems may be found in papers by Jacobson and Langmuir (1970) and Langmuir (1971). The groundwater system in the carbonate rocks of Centre County is described in some detail in Parizek, White, and Langmuir (1971).

Laboratory analysis has shown that the dominant anion species in solution is the bicarbonate ion (HCO_2^-). Neutral carbonic acid (H_2CO_3) and the carbonate ion ($CO_3^=$) occur in much lower concentrations. The pH of the solution (assuming that only carbonate reactions occur) is determined by the CO_2 pressure and by the amount of calcite ($CaCO_3$) in solution. Calcite concentration is a direct parameter that can be measured, whereas the carbon dioxide pressure must be calculated. The solution or evolution of CO_2 gas (equation 1) is sluggish and is often not at equilibrium. Geochemical analyses of carbonate groundwater usually consider the bicarbonate concentration and the pH to be the direct measurable parameters and then calculate an effective (or theoretical) CO_2 pressure through the use of equations 1, 2, and 3 assumed to be at equilibrium. Then, by comparing the calculated CO_2 pressure in the water with the carbon dioxide gas pressure expected from various environments, some guess as to the source of the water can often be made.

Groundwater is often not at equilibrium with the limestone wall rock. The calculated ion activity product defined by equation 6 is a good test of equilibrium. The calcium ion concentration can be measured directly and the carbonate ion concentration calculated from the pH and bicarbonate ion concentration using equation 4. The ion activity product is calculated from equation 6 and compared with the solubility product constant. If the experimental ion activity product is less than the solubility product, the water is undersaturated and can dissolve more calcite. If it is greater than the solubility product the water is supersaturated and should precipitate calcite.

Measurements on a large number of water samples from springs and caves (Harmon et al., 1972) show that most waters from the cavern environment are in fact undersaturated. Only waters dripping from cave roofs are supersaturated and these measurements are subject to some doubt because of the possibility of degassing CO_2 while the water sample was collected from the slowly dripping stalactite. Of the two kinds of springs mentioned in central Pennsylvania, the diffuse flow springs tend to be near saturation but perhaps slightly undersaturated. The conduit springs are always undersaturated suggesting that water can move all the way through the open cave system without coming into complete equilibrium with the limestone wall rock.

Pure water at 10°C will dissolve carbon dioxide to a saturation limit of 0.75 ppm, in equilibrium with the $10^{-3.5}$ atm CO_2 partial pressure in the atmosphere. If such water is free of dissolved carbonates, the pH of the solution will be 5.62. Analyses of waters in the sinking streams of central Pennsylvania yield $CaCO_3$ concentrations of only a few ppm and pH values near 6.8. The water that enters the carbonate mass from sinking streams flowing from the border lands is thus in equilibrium with a low CO_2 pressure.

Rainfall on the limestone surface infiltrates through a soil horizon in most karst areas. Biological processes in the soil raise the carbon dioxide pressure in the soil air to values on the order of 10^{-2} to 10^{-1} atm. Infiltration water comes to at least partial equilibrium with the carbon dioxide-rich soil atmosphere before entering the underlying limestone.

Waters which enter the carbonate rock mass can thus have a very diverse chemistry depending on their origin. Sinking stream waters pick up $CaCO_3$ from contact with the wall rock of the solution channels but saturate at relatively low concentrations because of the low initial CO_2 pressure. Vertically moving water from the karst surface picks up much $CaCO_3$ from the soil mantle and may even be saturated with respect to the higher CO_2 pressure before it enters the bedrock itself. Depending on the hydrogeology of the drainage basin, other sources of water such as waters from vertical shafts, waters from base level backflooding, and waters that seep in vertically from overlying aquifers all mix and make up the carbonate groundwater body. The process of cave development is thus complicated because the effectiveness of solution will depend to some degree on the source of the water.

Bögli (1964) has called a great deal of attention to what has come to be known as the *mischungskorrosion* effect. The change in $CaCO_3$ content with pH or carbon dioxide pressure is not linear. It is possible to mix two waters, one saturated at a high carbon dioxide pressure and one saturated at a low carbon dioxide pressure and obtain a mixed water that is undersaturated with respect to $CaCO_3$. This mixed water is capable of dissolving more limestone. Such mixed water zones occur near the water table where the laterally moving water from the sinking streams meets the vertically moving water from the overlying limestone soil. Bögli has emphasized that the zone of mixed water is one way of accounting for the concentration of caves near the water table. It certainly does provide an attractive hypothesis for the formation of joint-controlled wall and ceiling pockets. One can easily imagine a water of a specified chemistry seeping from a joint to meet water of a different chemistry flowing in the main cave passage. A mischungskorrosion zone is developed locally and dissolves away the limestone later observed as the solution pocket.

Determinations of the geochemistry of cave waters does show that Davis' original reasoning for the two-cycle hypothesis was incorrect. Davis could only explain the solution of limestone in the lower parts of a cave while deposition was going up in the upper parts of the cave by a two stage history. Actually, the laterally moving waters of the karsted carbonate aquifer are nearly always undersaturated and can thus dissolve limestone to form cave passages. The soil waters dripping through the cavern roof are always supersaturated and can deposit travertine with only the requirement that the cave atmosphere be able to accept the lost CO_2. Solution and deposition can go on simultaneously using waters of two different chemistries. No special relationship to a cycle of uplift and erosion of the land surface is required.

The flow of groundwater in porous media aquifers such as sandstones and glacial gravels obeys Darcy's Law: the velocity of flow is directly proportional to the hydrostatic head. Velocities are very low, on the order of feet per day or even feet per year if permeability or head is very low. The flow regime is strictly laminar; the water follows the flow streamlines and there is no turbulent mixing of waters.

Groundwater flow in a solution conduit is often turbulent. The onset of turbulence is characterized by the dimensionless Reynolds number

$$N_R + \frac{VR}{\nu}$$

where V is the velocity, R is the hydraulic radius (equal to the diameter in the case of pipe flow), and ν is the kinematic viscosity. Turbulence sets in at about $N_R = 2000$ for smooth pipes and there is a considerable transition region before fully developed turbulent flow is observed. Smith and Sayre (1964) considered turbulent flow in normal groundwater situations and concluded that turbulence is unimportant except possibly in coarse-grained gravel aquifers.

Limestone caves are another matter. Scallop patterns establish that flows in many cave passages reach values of 0.05 to 1.0 feet/sec, many times faster than flow in porous media aquifers. Under these conditions, turbulence will set in at passage diameters on the order of a few inches. We must then take into account the fact that the flow in the proto-cave passage will become turbulent while the passage is still very small. Indeed it could be argued that a passage size somewhere between a few tenths of an inch and a few inches marks the transition from the noncavernous to the cavernous aquifer.

The existence of cavernous openings in the limestone has a profound effect on the rate of flow of the groundwater through the aquifer and on the shape of the water table. The water table in karsted carbonate terrains is quite flat; gradients are often on the order of a few feet per mile. The water table surface does not mirror the surface topography as it does in homogeneous porous–media aquifers. The open channels of the cave system explains the flat gradients rather nicely. The system is open and the water easily runs out. A karsted carbonate aquifer simply cannot support a high gradient.

These hydraulic relationships cast a strong doubt on the basic premise of most of the classical theories of cave origin, namely that the position of the water table controls the zone of cavern development. The position of the water table appears to be a result of the development of a cavernous zone rather than the other way around. The water table is controlled by the position of the caves rather than the cave development controlled by the position of the water table.

One of the most remarkable aspects of cave development is the fact that caves occur as single passages. Caves are usually large conduits surrounded by massive limestone showing little modification by solution. Maze caves and spongework caves are the exception. An explanation for the existence of discrete passages was first provided by Kaye (1957). He showed that the rate of limestone solution increased as the velocity of flow increased. If we imagine an unmodified mass of limestone just exposed to solutional attack, it will contain many possible flow paths along sequences of joints, fractures and bedding planes. Just by random chance, one path or a few paths through this maze will have a lower hydraulic resistance than other possible paths. The optimal path will therefore carry a slightly larger flow at a slightly higher velocity than the alternative paths. The rate of solution in the optimal path will be larger and it will increase at a faster rate. The more rapidly growing optimal path garners still more water at the expense of alternative paths and thus grows at an accelerating rate. By the time the optimal path has grown to the dimensions of a cave, it has completely outrun its competitors and there is only one conduit among very minor joint and bedding plane openings.

This mechanism of channelization does not require the controlling influence of a water table. However, as the channel gains in size, flow becomes more localized and behaves more like an underground version of a surface stream. The channel may indeed lie just beneath the water table, but it is clearly carrying the bulk of the groundwater and the groundwater flow no longer has any resemblance to flow in a porous medium aquifer.

The Kaye "self-acceleration" principle may account for the localized solution activity that we call "caves" but there remain some problems with the detailed mechanism. The first is how the optimum path channel gets started in the first place. Imagine again an unmodified mass of limestone containing only the usual primary permeability and a certain amount of secondary permeability in the form of joints and bedding plane partings. The limestone mass is attacked by slightly acidic water either from precipitation on the limestone surface or from encroaching surface streams. If the chemical reactions previously described are rapid compared to the time it takes the water to percolate through the limestone, the water should very quickly become saturated with calcium carbonate and no further bedrock would be dissolved. The initiation of the conduit can only be explained if the kinetics of the chemical reactions are very sluggish.

Measurements of solution kinetics of limestone were made by Weyl (1958) who showed that the approach of the water to saturation was logarithmic. Although the solution might reach, say, 90% of the saturation concentration rather quickly, it would take much longer to reach 99% saturation. Solution along the flow path in the original rock mass would be slow but would take place. As the proto-cave became larger, more water would move through it; the water would be moving faster and could thus penetrate farther through the aquifer undersaturated, and in general the solution process would speed up. It is thus possible to account for cavern development beneath impermeable caprocks where water from above does not penetrate.

A second problem in the "self-acceleration" mechanism is the role, if any, of turbulent flow. White and Longyear (1962) argued on qualitative grounds that the onset of turbulence would greatly accelerate the solution process because the turbulent mixing would increase the solution rate. More quantitative calculations since then have been equivocal. The most elaborate model (Curl, 1965) predicts no important effect of flow velocity on solution rate. The problem has not been resolved. If kinetics are not affected by flow velocity and more importantly by the onset of turbulence, the common occurrence of single conduit caves and the relative rarity of maze caves becomes very difficult to explain.

STRUCTURAL AND STRATIGRAPHIC CONTROLS

A major shortcoming of the classical theories of cave origin is the minor role assigned to the structural and stratigraphic setting in which the caves occur. Many of the theoretical models assumed massive, flat-lying limestones with little consideration of the position of these limestones in the stratigraphic column. If we consider cave development as a process, in which groundwater guided by hydraulic laws flows through the limestone bedrock and dissolves carbonate minerals according to some rate law determined by both reaction kinetics and flow hydraulics, then we could visualize conceptually some sort of differential equation that would describe these processes. All differential equations have an infinity of solutions. The solution appropriate to a particular problem is determined by specifying boundary conditions. The stratigraphy and structure are the geological boundary conditions. It is really stratigraphy and structure that determine the location, orientation, and pattern of caves.

Major structural and stratigraphic features, folds, faults, and the thickness and placement of the carbonate rocks in the stratigraphic section, mainly serve to determine what may be called the hydrogeologic setting. The hydrogeologic setting determines how the carbonates are arranged in the drainage basin which in turn determines types and location of recharge points, hydraulic gradients, and possible discharge points. Size, location and orientation of caves are determined by these factors.

The role of the hydrogeologic setting is particularly important in Pennsylvania. The cavernous Ordovician limestones are exposed in the Nittany and Kishicoquillas Valleys on the crests of anticlines. They, therefore, occupy the valley floors and the recharge is from the clastic rocks that make up the intervening mountains. The main types of Ordovician limestone caves are the stream inlet caves (Sharer, Veiled Lady, and Miller caves in Centre County, or the Nails Caves in Mifflin County, for example) located where the mountain streams sink, or stream outlet caves which are either present-day conduits feeding big springs or abandoned conduits (Penn's Cave in Centre County, Alexander Caverns in Mifflin County, Indian River Cave in Blair County, for example).

In contrast to the Ordovician limestones, the Helderberg group of carbonates is mainly exposed on the flanks of folds along the sides of subordinate ridges. This location arises because of the stratigraphic position of the Helderberg, directly below the Oriskany sandstone which is usually the resistant layer holding up the ridge tops. Further, since the Helderberg is only a few hundred feet thick it forms only narrow bands of outcrop. For the most part there is no concentrated stream input and the Helderberg caves seem mostly to be the result of more slowly circulating groundwater and to date back to the time of dissection of the ridges.

Joints appear to be the primary paths through which the initial groundwater circulates. In the folded Appalachians there are generally two joint directions (or sets), one paralleling the valleys (and thus the regional structure) and the other perpendicular to the first. The strike joints are tension joints in the crests and flanks of the valley anticlines and would be expected to be more open than the perpendicular dip joints. This is generally borne out by the cave patterns. Most of the linear caves in folded limestones are oriented along the strike and appear to be guided by strike joints. Angulate caves have their greatest elongation along the strike. Passage cross sections of angulate caves are larger in the strike-oriented segments and smaller in the passages that cut across the structure.

Deike (1969) carried out a formal statistical analysis of the cave orientations of a set of 27 caves in central Pennsylvania. She devised a method for representing the cave by an orientational rosette similar to the rosettes used to represent joint sets. The cave map was marked out in segments. The orientation of each segment was then measured and the accumulated passage length in each interval of arc was plotted on polar coordinate paper. The cave rosettes could then be compared with rosettes prepared by plotting the number of joints in each orientational segments, and agreement was found to be very good.

It seems likely that clusters of joints (fracture traces) are even more important as primary routes for groundwater movement. Fracture trace intersections can be used to locate high yield water wells in the noncavernous dolomites and other aquifers of Pennsylvania (Lattman and Parizek, 1964). It seems likely that investigation of fracture traces to locate caves would also prove helpful, but this technique has not been tested.

Bedding planes can also serve as primary routes for groundwater movement. This is particularly true in the Helderberg limestone caves. Certain of these, for example Hesston Cave, Huntingdon County, are maze pattern caves along single beds in dipping limestone. Bedding plane partings, however, are certainly less important than joints and fractures in the folded Appalachians. This is in contrast to caves in the flat-lying limestones of West Virginia, Indiana, and Kentucky, where bedding planes seem to be the most important for determining initial groundwater routes.

The lithologic and stratigraphic controls take three forms: the presence of thin beds of non-carbonate rock within the carbonate section (thin shales, sandstones, and the like), the presence of dolomite rather than limestone, and the variation in the chemical composition and petrographic character of the limestone itself.

The role of non-carbonate beds is mostly to seal off the limestones or to provide diversion for groundwater flow. The Salona and Coburn formations at the top of the Ordovician limestone section have one to two-inch shale layers every foot or so and are essentially non-cavernous. They also give poor well yields. Likewise the shaley limestone units at the bottom of the Tonoloway limestone is non-cavernous compared to the overlying Helderberg, probably because of the large amount of shaley material which impedes groundwater flow, probably retards solution kinetics, and tends to seal any solution openings that may form with a clay residue. On the other hand, the presence of clastic material in the limestone need not be a hindrance to cavern development. The outstanding example is the Loyalhanna limestone of western Pennsylvania that contains more than 50% quartz sand and should technically be considered a sandstone with a sparry calcite cement. The Loyalhanna contains the largest cave in the state, Laurel Caverns, and many other large caves. In this case the solution of the cement can take place while the sand must be removed mechanically. However, the presence of the porous residual sand does not impede the circulation of groundwater and the continuous removal of the cement.

The dolomites of central Pennsylvania, the Gatesberg and the Beekmantown particularly, are almost non-cavernous although they are good aquifers. The reasons for this are largely unknown, although they might have to do with the solution kinetics which appear to be more sluggish for dolomite than for limestone. However, it is peculiar that the Pennsylvania dolomites are non-cavernous while large caves are known in dolomites in Tennessee (the Knox Group) and in Missouri.

More subtle is the influence of other chemical and petrographic factors on the amount of cave developed in particular limestone horizons. The amount of cave volume distributed in the upper 1400 feet of Champlainian limestone is shown in Figure 17 (Rauch and White, 1970). It can be seen that nearly all the Ordovician limestone caves are distributed between the Nealmont, Snyder, Benner, and Grazier limestones. Furthermore, the purest carbonate rock in the valley, the Valentine limestone, is poorly cavernous. Since these limestones crop out on the flanks of anticlines and dip toward the mountain ridges from which the recharge water comes, the distribution in Figure 17 is a fair test of relative solution rates since all beds are equally susceptible to groundwater infiltration. Factors which seem to promote cavern development are micrite cements of small grain size, a magnesium concentration in the range of 4 weight percent, and a low concentration of alumina.

BASE LEVEL CONTROLS

The rapid draining of cavernous zones in carbonate aquifers leads to very flat water table surfaces. Calculations also show that the rate of cavern development under optimum conditions is rapid compared with

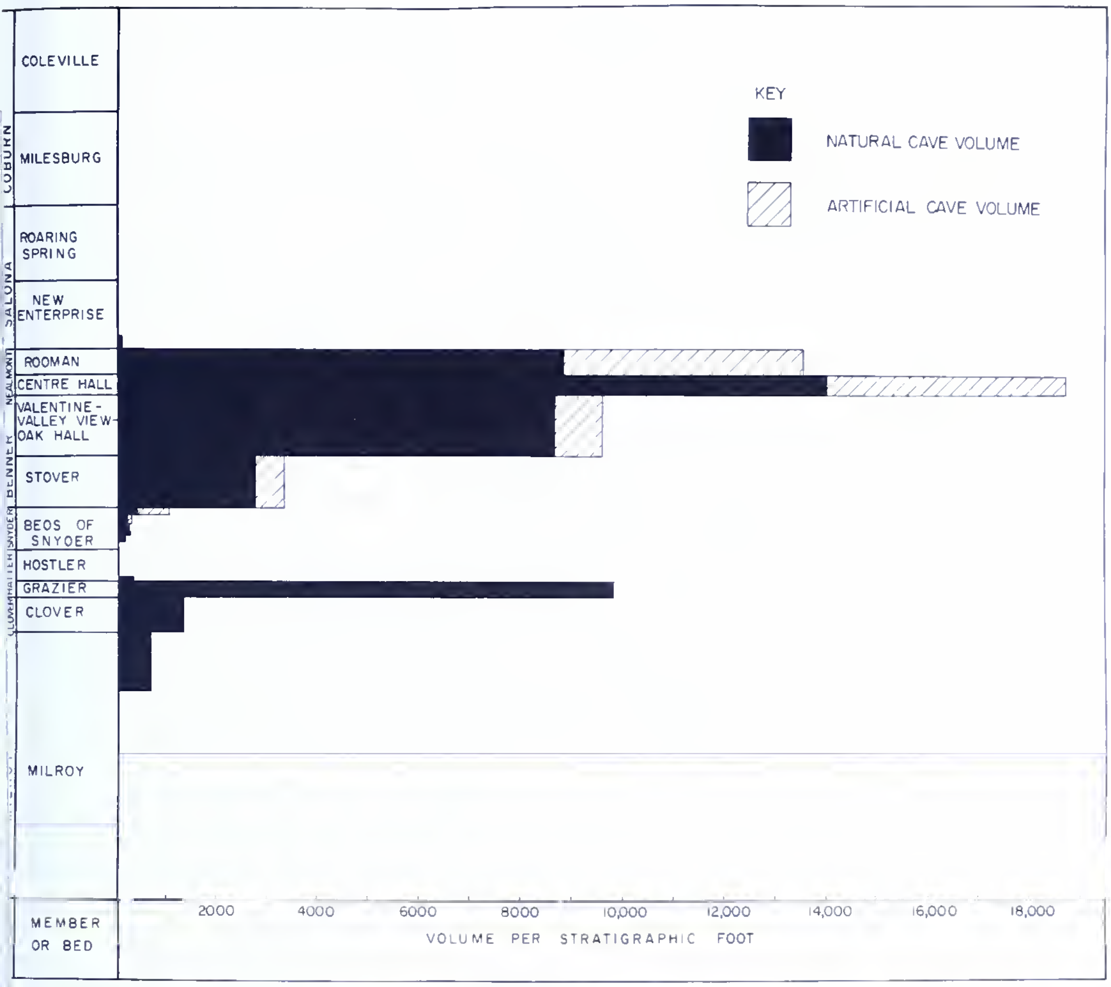


Figure 17. Distribution of cave volume compared to stratigraphic unit. (Adapted from Rauch and White, 1970.)

the erosional downwasting of non-carbonate rocks. The result is a network of pipes and channels more or less graded to the surface streams into which the underground systems drain. The downcutting of the surface stream is the rate-limiting process. The phrase "more or less graded" does not imply uniform slopes toward the surface stream as would be the case of a graded surface tributary. Many of the conduits are water-filled with flow driven by hydraulic gradients. The flow can therefore follow the optimum hydraulic path around structural and stratigraphic barriers even when these require the flow to extend to some depths below regional base level.

The lack of graded floors on cave passages was one of Davis' most important criteria for arguing against a vadose origin for caves. However, the lack of a graded floor, particularly over the short distances that can be observed in most caves, is not a proof for a deep circulating groundwater. A drainage system of water-filled tubes with perhaps some channels with free-surface streams could also be non-graded over short distances and still maintain an average regional slope toward the discharge point controlled by local base level.

If regional base levels lowered uniformly because of uniform downcutting of the surface streams, one would expect to find caves with a rather complex vertical development, some with high canyons as underground streams cut deeper to keep up with the surface streams, some with superimposed sequences of tubes as underground flow is pirated to lower and lower levels. All these things are found, but not commonly.

Cave passages tend to be horizontal or nearly so, and to be elongate along the strike. Furthermore, caves tend to occur more frequently at some elevations above base level and to be sparse or nonexistent at other elevations, even when the availability of limestone is uniform. Figure 18 shows the distribution of cave length with elevation in the southern Cumberland Valley. There are pronounced maxima in the amount of cave development at elevations of 500 and 600 feet. Similar results were found for the entire Potomac River basin (White and White, 1975). A similar study in central Pennsylvania (Rauch, 1969) showed that cave development occurred mainly at a single elevation unique to each limestone valley. All this is evidence that downcutting of surface streams is not uniform and that the concentrations of cave development at particular elevations are mapping pauses in the regional downcutting just in the same way that river terraces record pauses in the lowering of base level.

Other evidence for cave development in a shallow zone close to regional base level is provided by the patterns of the caves themselves. The pattern is strongly a function of the dip. Maze caves tend to form only in relatively flat limestones. When the maze caves form in dipping beds, the plane of the cave parallels the dip but passages terminate in both up-dip and down-dip directions, implying a restricted range of elevations over which solutional enlargement takes place. Cross-sections of passages in nearly vertical limestones show that solution terminates in a distinct ceiling, although there are no lithologic barriers to continued solution along the bedding planes (White, 1960).

The observation that caves appeared to be correlated with definite erosion surfaces was first noted by Sweeting (1950) for caves in the Ingleborough district of Yorkshire. At about the same time Davies noted the horizontal caves and their apparent relation to river terraces in the Appalachians (Davies, 1953, 1958), which he eventually formulated into a theory of cave development in folded limestone (Davies, 1960). Davies' 1960 paper is important because it marks a transition from the physiographic theorizing and qualitative reasoning of the "classic" theories previously discussed to the more quantitative process

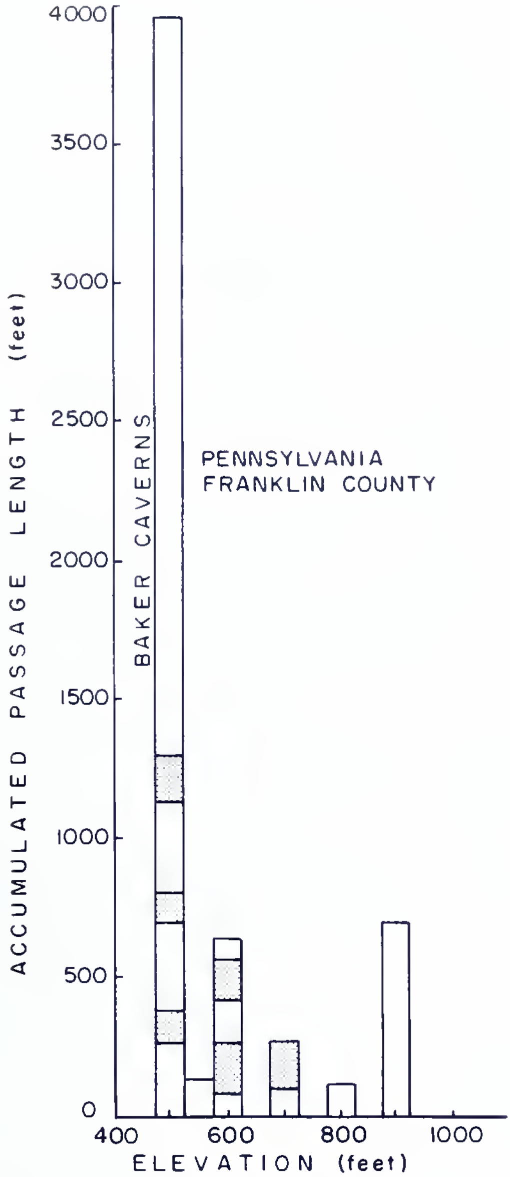


Figure 18. Distribution of cave length versus elevation in the southern Cumberland Valley. (Adapted from Rauch and White, 1970.)

approach. He was very much aware of the geological boundary conditions on cavern development. Davies' theory proposes four stages in cavern development:

1. Random solution at depth. Small tubes, pockets, widened joints and bedding plane partings are developed by percolating groundwaters at depths below the water table.

2. Integration and mature development of solution openings. Main cavern development takes place near the top of the water table by groundwater moving toward regional outlet points controlled by the position of local base level. Mature cavern development requires a period of base level stability, which in turn implies a widening of surface valleys and thus a concordance between zones of extensive cave development and terrace development in the surface valleys.

3. Deposition of fill. Cave fills, mainly clastic material are deposited toward the end and after the integration of cavern passages.

4. Uplift and erosion. With the end of stable conditions the cavern passages are raised above the level of the water table and become air filled. In this stage the deposition of travertine occurs and there is erosion of the fill material. Ultimately there is complete destruction of the cave by collapse and erosion.

Davies' theory, it can be seen, is a development of Swinnerton's ideas. It is still much entangled with the water table as a primary cause (rather than an effect) of cavern development. As a description of the events that took place in most Pennsylvania caves, it is reasonably accurate. Describing the chemistry and physics of the cave-forming process modifies the details but not the overall picture.

CHEMICAL DEPOSITS IN CAVES

Perhaps the most attractive features of caves are their mineral deposits. In the constant environment of the cave, mineralization processes can proceed uninterrupted over long periods of time. The result is a wide variety of mineral features known as "cave formations" or in more recent literature as "speleothems." The section that follows discusses those minerals that occur in Pennsylvania caves and some of the speleothem forms. More complete lists (Moore, 1970, Broughton, 1972) show that more than 80 different mineral species have been found in caves. Most of these, however, require rather special conditions or rather special water chemistry. The discussion is limited to the more common minerals that would be expected to deposit from cold limestone groundwater.

CARBONATE MINERALS AND MINERAL DEPOSITION

The most abundant species in limestone groundwater are Ca^{++}, Mg^{++}, and HCO_3^-. It is not surprising, therefore, to discover that carbonate minerals make up the bulk of cave deposits. The carbonates that form in caves are listed in Table 1. All are white crystalline materials and identification can be done reliably only by X-ray diffraction. Calcite is by far the most common. Probably 90% or more of all

Table 1. ***Carbonate Minerals Reported from Caves***

Mineral	Formula	Crystal System	Space Group
Calcite	$CaCO_3$	Rhombohedral	$R\bar{3}c$
Aragonite	$CaCO_3$	Orthorhombic	Pmcn
Dolomite	$CaMg(CO_3)_2$	Rhombohedral	$R\bar{3}$
Huntite	$CaMg_3(CO_3)_4$	Rhombohedral	R32
Hydromagnesite	$4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O$	Orthorhombic	$C222_1$
Nesquehonite	$MgCO_3 \cdot 3H_2O$	Monoclinic	$P2_1/c$

speleothems are composed of calcite. Aragonite occures in many Pennsylvania caves. Dolomite, huntite, and the hydrated magnesium carbonate minerals are rare.

The process of calcite deposition is the reverse of calcite solution and the equations listed earlier apply. The source of water and carbon dioxide is the infiltration water from the soils that overlie the cave. The chemical steps in the process are shown in Figure 19. Rainfall seeps into the soil where biotic activity is high. The carbon dioxide pressure in the soil may reach values as high as 0.1 atm. The soil water becomes very acid but (if the soils are depleted in calcium carbonate) accumulates little dissolved carbonate. Continuing its downward course, the water then reaches the broken rock mantle zone at the base of the soil. Here it reacts with the carbonates in the mantle material and approaches saturation between $CaCO_3$ and the high CO_2 partial pressure. A considerable quantity of calcium carbonate is taken into solution. The downward percolating water now leaves the soil and mantle zone and makes its way into the limestone bedrock along joints and fractures. Because no additional carbon dioxide is available at depth and because the water is already highly saturated, the solutional attack on the joints and fractures is likely to be small. Solutional modification of these diffuse flow paths takes place very slowly or in situations where the reactions in the mantle did not go to completion. Now suppose that the joint intersects the roof of an underlying cave passage. The cave atmosphere has a CO_2 pressure perhaps an order of magnitude higher than that of the surface atmosphere but much smaller than the CO_2 pressure of the seeping water. The water percolating through the cave roof is highly supersaturated with respect to the cave atmosphere. The CO_2 is therefore degassed from the dripping or seeping water into the cave atmosphere, building up the necessary supersaturation in the solution necessary for carbonate minerals to deposit.

The model described above was proposed by Holland and others (1964) to explain carbonate deposition in Luray Caverns. It seems to be widely applicable. The CO_2-loss model provides an explanation for the observation that the cleanest, most coarsely crystalline, and seemingly, the most rapidly growing dripstone occurs where evaporation is negligible. Caves without entrances (which have been opened by excavation of some sort) or segments of cave channel blocked by water traps are known to contain some of the most spectacular speleothems. Evaporation can also cause deposition, as indicated on the figure, but apparently interferes with the growth of high quality crystals.

The orthorhombic polymorph of calcium carbonate, aragonite, occurs rather frequently in caves. Sometimes it appears as clusters of acicular crystals known as anthodites. More commonly, it is incorporated with other dripstone deposits, often interlayered with calcite. The difficulty is that aragonite is not thermodynamically stable under cavern conditions. It is a high pressure polymorph and should occur at cave temperatures only at pressures in excess of 5000 atmospheres. For all of that, aragonite is a common mineral in cave deposits and in carbonate sediments. Arguments have raged for years over the reasons for the metastable precipitation of aragonite in marine and fresh water environments. Much of the relevant data is summarized by Curl (1962).

The solubility curve for aragonite is shown in Figure 19. Aragonite deposition requires only that the solution be more than about 10% supersaturated with respect to calcite. It is known that impurity ions such as Sr^{++}, SO_4^{-2}, and perhaps Mg^{++} enhance the deposition of aragonite and they apparently do this through the inhibition of calcite deposition. By retarding the growth of calcite through poisoning of the growth surfaces, the necessary supersaturation for aragonite deposition can build up.

Dolomite has not been reported from a Pennsylvania cave nor, for that matter, from many other caves. Although it is a common constituent of carbonate rocks, dolomite does not precipitate readily from fresh-water solutions even when these solutions are rich in Mg^{++}.

Huntite and the minerals hydromagnesite and nesquehonite occur as fine grained white powders known collectively as "moonmilk." Moonmilk is usually wet and appears as a pasty white mass with the texture of cottage cheese. Dry moonmilk is a loose plaster-like powder. The individual mineral grains are extremely small—on the order of one micrometer—so that individual grains are just barely resolvable in a microscope. Moonmilk may also be composed of calcite or aragonite. It is not common in Pennsylvania caves, although small quantities have been found in the Ordovician limestone caves of the central part of the state.

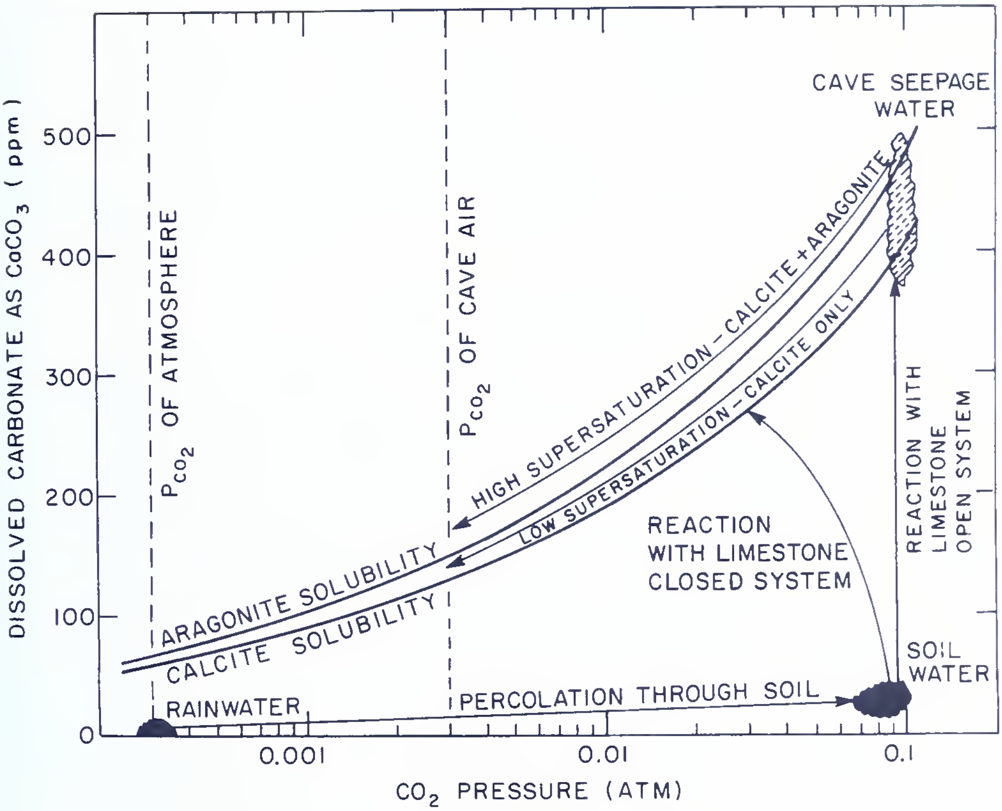


Figure 19. Solubility curves for calcite and aragonite showing the chemical evolution for speleothem-depositing vadose water.

OTHER MINERALS

Sulfate minerals are common in many caves in the Interior Lowlands Province: gypsum, epsomite, mirabilite, celestine, blödite, and other sulfates. Only gypsum, $CaSO_4 \cdot 2H_2O$ has thus far been reported from a Pennsylvania cave. It appears as clusters of needles growing from the soils of some of the Vanport limestone caves but occurs in very sparse amounts. It seems likely that the source of the gypsum is from the oxidation of sulfides in the shale and coal strata that overlie the Vanport, a mechanism similar to that proposed by Pohl and White (1965) for the gypsum deposits of the central Kentucky karst.

Iron oxides are sometimes brought into the cave either as fine particles in suspension or as a ferrous iron-containing solution that oxidizes and precipitates the ferric oxide and oxide hydrates in the cave. The iron oxide takes the form of rather poorly consolidated stalactites. The mineral grains are usually too poorly crystallized to diffract X-rays and thus would be considered as limonite or perhaps a poorly crystallized goethite (FeOOH).

Ice would be considered a cave mineral. It forms near the entrances of many Pennsylvania caves during the winter sometimes in the form of spectacular stalactites and stalagmites. However, in all Pennsylvania caves ice is ephemeral and melts out during the summer, although in a few caves which act as cold air traps (glacieres) it persists into late spring or early summer.

SPELEOTHEMS

Mineral-depositing solutions move vertically through the vadose zone under the influence of gravity. The mineral deposits left behind by dripping or flowing water, therefore, tend to take on shapes in which the gravitational control of the solution is much in evidence. Each mineral, however, has a characteristic growth habit. Certain crystal forms are preferred above others and certain crystal directions grow faster than others. Calcite, for example, grows faster in the c-axis direction. Modification in the chemistry of the solution or in the rate of deposition can modify the habit or can change the relative rate of growth in different crystallographic directions. There is thus a competition between shapes guided by the flow path of the solution and shapes guided by the particular mineral and its crystallization habit. This gives rise to two broad classes of speleothems, dripstone and flowstone forms, and erratic forms. Within the context of these basic mechanisms, there is an immense and indeed continuous variety of shapes for the travertine deposits depending on the vagaries of exact flow path, flow rate, chemical characteristics of the water, and relative humidity and CO_2 pressure of the cave atmosphere.

Because caves, particularly commercial caves, derive much of their charm from speleothems, these deposits have gained many fanciful names. Rather complete descriptions of speleothems may be found in the Hill's (1976) field guide to cave minerals. We use here a two-level system of classification and speak of the *form* of a speleothem as the shape that can be distinguished by growth habit or depositional mechanism. *Styles* are variants of the forms and can be described by adjectival modifiers in as much detail and complexity as seems useful. In this system a stalactite is a form, whereas a soda-straw stalactite refers to a specific style.

A listing of the most common speleothem forms is given below:

A. Dripstone and Flowstone Forms (gravity controlled)
    1. Stalactites
    2. Stalagmites
    3. Draperies
    4. Flowstone sheets

B. Erratic Forms (crystal growth controlled)
  1. Shields
  2. Helictites
  3. Botryoidal forms
  4. Anthodites
  5. Oulopholites
  6. Moonmilk

C. Sub-Aqueous Forms
  1. Rimstone pools
  2. Concretions of various kinds
  3. Pool deposits
  4. Crystal linings

Water emerging from joints in cave ceilings hangs there in drops for a short time before the drops fall to the floor. During the time in which the drop hangs, CO_2 is degassed, the solution becomes supersaturated and a small amount of mineral matter is deposited in a ring with a diameter similar to that of the drop. This ring grows downward at constant diameter as more material is deposited until a slender tube of calcite known as a soda straw stalactite is formed. The tube is somewhat porous, and water can seep between grains and along cleavage cracks to deposit minerals on the outside as well. Additional fluid from other joints may stream down the outside of the straw and also build up additional layers. The natural evolution of the stalactite is from the primary tube to a pendant form. As the stalactite grows, the central canal may become clogged and filled in but some trace of it usually remains. In cross section, stalactites have a series of concentric rings representing different concentrations of impurities and different rates of growth. They are not annual rings and in spite of several efforts, no good interpretation has been placed on them. Long term climatic variation in the cave region would be the most probable guess. Since the c-axis direction of calcite is the fast growth direction, the central straw is usually composed of calcite grains oriented with their c-axis along the straw axis. Grains that make up the outer layers may have their fast growth directions along the stalactite axis, perpendicular to it, or at random, depending on the rate of deposition. More details on the mechanism of stalactite growth may be found in Moore (1962). Many minerals other than calcite occur in stalactite forms; both aragonite and gypsum occur this way. Others are listed by Hicks (1950).

Stalactites fed by more than one drip point may grow into quite complex shapes. Water flowing over the outside builds up ribs and folds to yield the form known as the drapery. Water that trails along the underside of ledges or of other stalactites may build up a sort of unfolded stalactite in which the growth layers are linear and parallel to the ledge and which is known colloquially as the "bacon strip."

Water dripping to the floor of the cave loses more CO_2, deposits more minerals and builds up the mound-like masses of travertine known as stalagmites. If the cave is not at 100% relative humidity, evaporation will contribute to the $CaCO_3$ deposition also. Stalagmites have no central canal. In longitudinal section they appear to be built up of superimposed caps, thicker in the center and thinning toward the edge as the solution flowing outward from the drip point gradually is depleted in dissolved calcium carbonate. If the drip rate is constant, there will be an equilibrium diameter for the stalagmite determined by the drip rate and the amount of calcium carbonate in solution. Stalagmites are not limited by the amount of weight that can be suspended as stalactites are, and can grow to quite large sizes. Many are fed by more than one drip point and can take on more complex shapes or there can be one large core stalagmite with smaller stalagmites growing on it. Some common styles of stalagmites are sketched in Figure 20.

Solutions flowing down walls and over ledges deposit masses of travertine with the appearance of a waterfall of rock. These deposits are called flowstone and can be of very large volume.

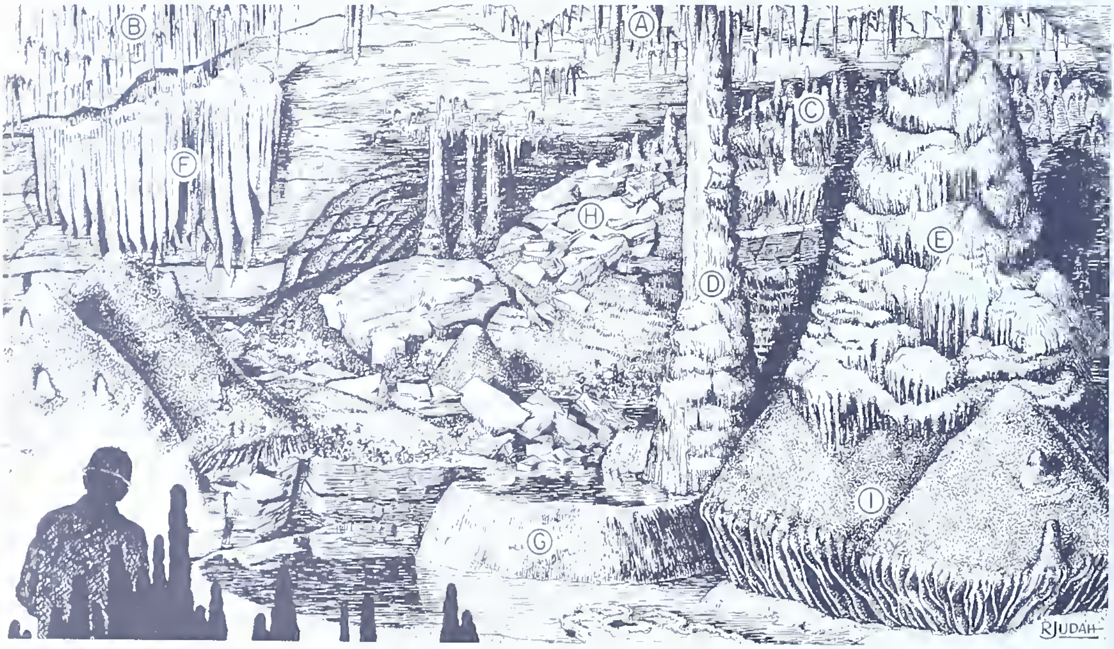


Figure 20. Idealized drawing of some common speleothems (sketch from Circular No. 8, Indiana Geological Survey, courtesy of J. B. Patton). A. stalactites, B. straw stalactites, C. stalagmites, D. column, E. tiered stalagmite, F. draperies, G. rimstone, H. breakdown, I. flowstone.

Shields are massive plates or slabs of travertine that jut out from cave walls at angles apparently determined by the arrangement of joints. They are a rare speleothem, occurring in great numbers in Grand Caverns, Virginia, and in Lehman Caves, Nevada. None has been recognized in Pennsylvania caves. Their relation to the local joint set has been described by Kundert (1952), and a theory for their origin has been proposed by Moore (1965).

Helictites are smooth-surface stalactitic forms that grow in curved paths instead of hanging vertically. Helictites have a central canal and appear to grow from the tip. They appear to form when flow rates through the canal are too slow to permit the formation of drops and are therefore controlled by the shifting orientation of the fast growth direction of the calcite crystal. Detailed mechanisms are unknown (Moore, 1954). Helictites occur in a number of Pennsylvania caves.

Botryoidal forms are small bead- or knob-like projections from cave walls. Globulite is a term used for the smaller ones. They are usually of calcite and are layered structures. However, the center of the layering is a small projection or growth point on the wall of the cave. Growth mechanisms are unknown except that they seem to be associated with fast moving films of water on cave walls. They are common in many Pennsylvania caves. A great variety exists in Lincoln Caverns.

The term anthodite has been applied to radiating clumps of crystalline aragonite. Typical anthodites grow in tufts of elongate acicular crystals radiating from a common center. Dendritic growth of individual crystals is common, resulting in a spiky appearance. It is not known how anthodites grow, although their appearance suggests that they must grow from the tip or else the dendritic pattern is difficult to explain. Likewise, there are transitional forms between anthodites and helictites with calcite overgrown on aragonite. Some contain tufts or lumps of moonmilk on the tips of the crystals, suggesting that the magnesium is the last material to precipitate from the evaporating solutions.

Oulopholites (gypsum flowers) are a form apparently unique to the sulfate minerals and require the different growth habit of the sulfates. In their most spectacular form, oulopholites consist of petals of gypsum growing outward from a common center. The petals are curved and are made up of bundles of individual gypsum crystals. They have much in common with the anthodites except that growth is almost certainly from the base. The petals of the flowers spread outward because of faster growth at the center of the cluster. This speleothem is best developed in the Mississippian limestone caves of Kentucky and Tennessee.

Concretions are roughly spherical unattached deposits that occur in pools or shallow basins. Several styles are found of which the smooth polished variety known as "cave pearls" have received most attention. The other common style is a rough, rather porous, structure. Both are layered structures and growth appears to take place around some piece of foreign material that acts as a nucleus. Concretions vary in size from fractions of an inch to several inches in diameter. The water dripping into the basins in which they form must agitate the water sufficiently to keep the speleothem from becoming cemented to the bottom. Other restrictions on flow rate or chemistry are not known.

Water collecting in pools continues to degas CO_2 from the pool surface. The supersaturated solution deposits calcite on the walls of the pool sometimes as rough, rather spongy deposits and sometimes as well-developed calcite crystals. A remarkable feature of cave pools is that some of them tend to be self-damming. Rimstone dams are travertine deposits, usually much thinner than they are high, and often with a complex convoluted pattern. Rimstone dams occur in many Pennsylvania caves where they usually reach maximum heights of a few inches. Dams are known, however, that reach heights of tens of feet. Calcite also tends to deposit outward over the surface of the pool forming lily pad-like masses.

A few instances are known in which a cave has been completely re-flooded after the excavation of the cave itself. If the re-flooding waters are supersaturated with respect to calcite, the entire cave interior may be lined with crystals. Crystal caves are uncommon and none are known in Pennsylvania.

CLASTIC SEDIMENTS IN CAVES

The process of karstification and cave development has thus far been treated as a process of solution. We have been concerned with the chemistry and hydraulics of groundwater interaction with a carbonate bedrock assumed to be perfectly soluble. Real limestones and dolomites are impure and contain from a few to perhaps 15% or more insoluble materials. Further, although sources of water from outside the karst area have been considered important, the role of these waters in transporting eroded non-carbonate rocks was neglected. The erosion products from border areas and from rocks overlying the carbonate sequence must also be transported by underground routes if there are no surface streams. It is these materials that make up the clastic sediments observed in caves.

CLASSIFICATION AND DESCRIPTION OF CLASTIC SEDIMENTS

All materials that have been placed in their present location in the cave by mechanical (as opposed to chemical) processes are considered clastic. These materials can be subdivided into two broad categories: those that are derived locally within the cave, and those that are transported into the cave from somewhere else. Within each of the main categories are several distinguishable classes of materials as listed below:

- A. Autochthonous (locally derived) Deposits
  1. Breakdown
  2. Weathering detritus
  3. Organic debris
- B. Allochthonous (distantly derived) Deposits
  1. Infiltrates
  2. Fluvial sediments
  3. Eolian sediments

Breakdown is the residual pile of bedrock fragments that result from the failure of cavern roofs and walls. According to the classification of Davies (1949, 1951) failure of massive beds along bedding planes or failure of whole sequences of beds at once gives rise to block breakdown. Failure of single thinner beds yields slab breakdown. Small shards and fragments that have not separated along bedding planes constitute chip breakdown. Block and slab breakdowns often break along joints or other pre-existing structural weaknesses. It is possible to analyze roof failure by the mechanics of fixed and cantilever beams. For any given thickness of bedding there will be a maximum span (passage width) beyond which the ceiling bed will not support its own weight (Figure 21). The analysis is for horizontal beams, which means horizontally bedded rocks. Pennsylvania caves which occur predominantly in folded rocks are more susceptible to breakdown. In the ceilings of strike passages in dipping beds such as are illustrated in Figure 8, the bedding plane forms one plane of weakness, the perpendicular joint another, and long triangular prisms of rock easily detach themselves from the ceilings. This type of breakdown is common in caves in folded limestone and gives rise to the characteristic cross section illustrated.

White and White (1969) tabulated some seven processes that trigger breakdown. These are (i) initial draining of the cave with resultant loss of buoyant support; (ii) base level backflooding during the time in which the cave is subject to annual flooding; (iii) undercutting of walls by free-surface streams that later make use of the open passages; (iv) action of surface waters weakening roofs in the later stages of the cave's history when the land surface is lowered; (v) action of vertical shafts which may remove parts of walls and other breakdown which may be supporting the roof; (vi) wedging, and chemical attack by minerals, mainly sulfates, forming in the bedrock; (vii) frost wedging near entrances.

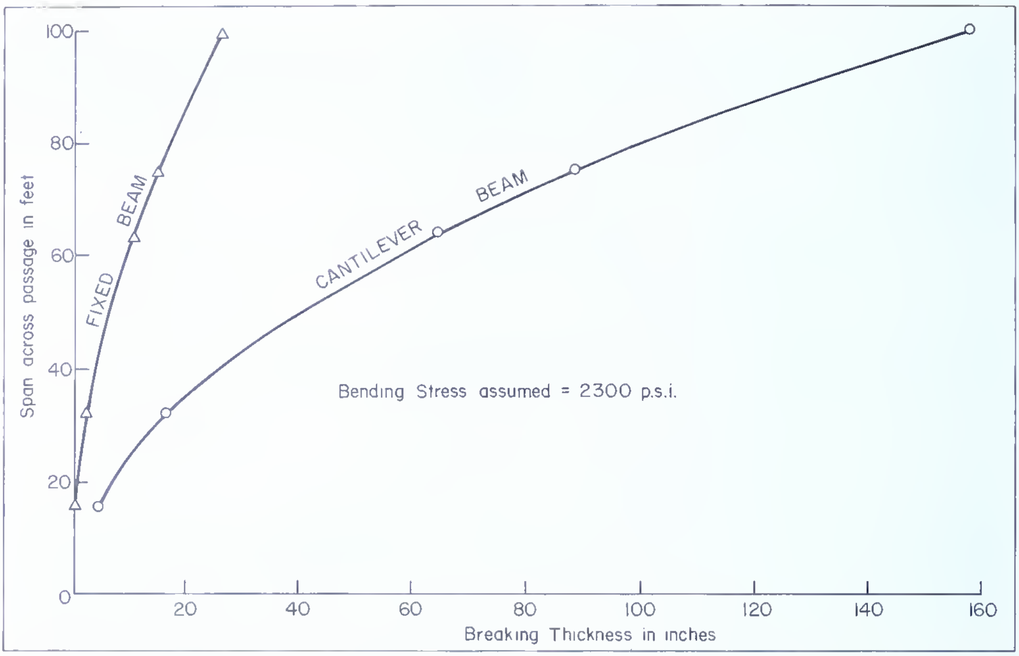


Figure 21. Critical thicknesses for fixed and cantilevered ceiling beams.

Weathering detritus is the residual material left behind when the limestone walls are dissolved. The main mineral constituent is quartz. Quartz occurs as chert nodules common in many limestones, silicified fossil fragments, and grains of quartz sand. Indeed, examination of a number of fills from Pennsylvania and Kentucky reveals that the bulk of what the cavers call "mud" is actually quartz. Clay minerals, kaolinite, montmorillonite, and illite occur but are a smaller fraction of the bulk sediment. The Loyalhanna limestone caves in western Pennsylvania have an exceptionally large burden of weathering detritus because of the nearly 50% sand content of the limestone.

Organic debris is the droppings of birds and bats which in some caves makes up a distinct stratigraphic sequence and has in addition a distinct phosphate mineralogy where the leaching solutions interact with the limestone wall rock. Guano caves are common in the southwest, in the Caribbean, and in South America. This sediment is of relatively minor importance in Pennsylvania.

Broadly, there are two ways in which insoluble materials can be transported into a cave depositional site: horizontally and vertically. The infiltrates are clastic materials transported vertically under the direct influence of gravity with or without the aid of flowing water. Soils in karst regions are washed, piped, or slumped into open crevices and sinkholes. They are eventually discharged into the cavern system without much chemical modification. Solution crevices, chimneys and vertical shafts reach through the cavernous bedrock and break through to the surface. Fragments of overlying bedrock and surface debris fall down these openings to become part of the infiltrate sediment. Cave entrances are also sites of intense erosion because of frost pry and freezing and thawing of the rocks and soils upslope. Horizontal entrances usually lead to the top of an entrance talus cone of varying height down which one must descend to the cave passage. Entrance talus materials are a mixture of breakdown and infiltrated debris. The infiltrates are exceptionally important sediments because they contain most of the fossil and archeological remains. Animals fall down sinkholes and become buried in the accumulating sediment. The gradual accumulation of entrance talus buries the camp sites of primeval man. The New Paris Sinks in Bedford County (Guilday, Martin, and McCrady, 1964) are among the most important Pleistocene vertebrate deposits known and they are shaft deposits of the types described above.

Fluvial sediments, stream-borne deposits, which may be transported through filled pipes as well as in open channels, make up the greatest part of most cavern sediments. They are derived from many sources. Some are re-worked autochthonous deposits, some have been derived from rocks higher in the stratigraphic column, and some have been transported from non-karstic border lands by sinking streams. The material usually consists of stream-rounded rock fragments, sand, silt, and clay. The finer grain-size material cannot usually be distinguished from weathering detritus or the infiltrates without extensive analyses. The composition and grain size merely reflect the character of the surrounding bedrock and the load-carrying capacity of the cavern streams. In the Appalachian caves, sandstone, cobble, and boulder fills sometimes occur in thicknesses of tens of feet.

Fluvial sediments occur in stratigraphic sequence and these strata are sometimes exposed where later free surface streams in the cave have cut through them. The Appalachian sequence is frequently one of silts, sands, and gravels in various combinations, but the topmost bed is often a fine clay reflecting quieter water conditions as the passage filled with sediment. This top layer of clay seems to have misled Bretz (1942) because the "red unctuous clays" that are an important middle stage in his sequence of cavern development do not exist in Pennsylvania, the Appalachians, or for that matter, much of anywhere else. It would be pleasing to think that the complex sedimentary record in many Pennsylvania caves could be used to decipher the Pleistocene history of the region. Unfortunately, such attempts as have been made have not come to any useful conclusions. A careful examination of the facies relations in clastic sediments of a single passage in the Flint Mammoth System of Kentucky showed that the section changed considerably over very short horizontal distances and that it was impossible to trace individual beds, much less interpret the entire section. The same situation occurs in Milroy Cave, Mifflin County, according to the results of Ogden and Ebaugh (1972) (Figure 22).

The third and last type of allochthonous deposits is the eolian or windblown type. Such materials are mainly loess and are important as a sediment in some caves of the mid-west. They have not been recognized in Pennsylvania.

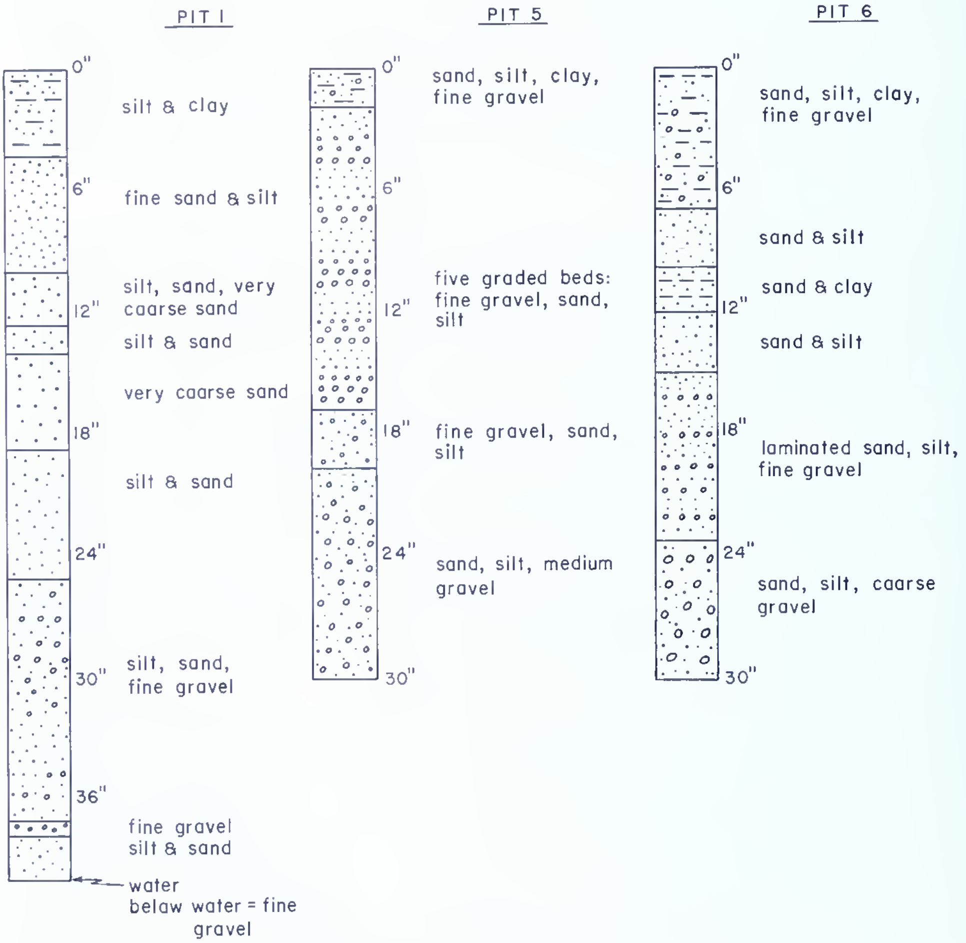


Figure 22. Sediment depositional sequences for Milroy Cave, Mifflin County.

SEDIMENT TRANSPORT AND ITS HYDROLOGICAL SIGNIFICANCE

We are concerned here only with the fluvial sediments because only these are transported long distances through the karst drainage basin. There are two mechanisms by which the clastic materials can be moved: as bedload and as suspended load. Bedload transport involves the tumbling of sedimentary particles along their bed by the shearing action of the water flowing above. It can either be a particle by particle tumbling in low flows or a massive movement of the entire bed when the stream is in full flood. It is not really relevant whether the flow is laminar or turbulent; the critical parameter is the shear force which is related to the velocity. Both theoretical calculations and laboratory measurements agree that velocities in the order of tenths of feet per second are required to move bed material. Intermediate sediment sizes, in the sand range, move most easily. Smaller particles tend to stick together and are difficult to break apart and move. Larger particles, in the gravel and cobble range, obviously require larger velocities. Motion of material as suspended load requires that the flow be turbulent because it is the turbulent eddies that keep the particles in suspension. In general, suspended load transport is a less effective way of moving sediment and only the finer particles are transported this way. Settling of particles carried in suspension does, however, account for the clay fills often found in the smallest cracks and pockets in cave systems. Mechanisms of cave sediment transport are described in somewhat more detail by White and White (1968).

Winnowing and differential transport of bedload sediment in open channel flow results in a stream bed armoring by the larger pieces of clastic sediment, mainly pebbles and cobbles. The armoring occurs in most cave stream beds. There exists, in fact, a complete set of underground bedforms that are similar if not identical to those found in surface streams: stream braiding, stream meandering, point bars, dunes, and cross-bedded sediments (Jones, 1971). Most bedforms that have been observed are in free-surface streams in open channels. Whether the same hydraulic geometries can be obtained in pipe-full conduits is another question and has not been answered.

A point that has been frequently overlooked in discussion of karst hydrology is the necessity of continuous transport of sediment in maturely karsted drainage basins. All weathering materials from the basin must be carried out of the basin through the cave systems. This applies to the materials eroded from the mountain ridges of central Pennsylvania where the small mountain streams sink at the limestone contact. It applies to the underdrained valleys with no surface streams. Since velocities in the fractional foot per second range are required to move the clastic materials, it follows that a complete karst system cannot function until the conduit network is sufficiently open and the velocities are sufficiently high to carry the sediment load. There must be, therefore, a balance between the amount of load to be carried (as measured by the clastic material dumped into the karst system from the outside and the amount of weathering detritus generated in the limestone itself) and the amount of water and the hydraulic gradient available to force it through the underground routes. This may be part of the explanation for why true karst systems never develop in some hydrogeologic settings. If the sediment load is too heavy and the amount of water and/or hydraulic gradient too small, the solution cavities that do form will be silted shut and streams will remain on the surface.

There exists also the possibility that clastic sediment transport is partly responsible for the development of the conduit systems close to regional base level. If we imagine the development of a three dimensional set of small tubes, crevices, partings, cavities at random depths in the early stages of groundwater circulation (Davies' Stage 1) by percolating water carrying no sediment load, the further enlargement of the openings near the surface will permit the injection of sediments which will tend to filter down and clog the lower openings. This would have the effect of forcing the remaining flow into more shallow routes where velocities, because of the restricted number of openings, would become high enough to transport the sediment.

Insoluble clastic sediment left as a veneer on the floors of passages may serve a role as perching beds. Since the master trunks form very close to base level and have low gradients they also have a poor sediment carrying capacity. As base level continues to lower through downcutting of surface streams, flow through these master conduits will be perched on the pad of fluvial sediment on the passage floor. The water cannot downcut by solution because it is not in direct contact with the limestone floor and it cannot downcut by abrasion because the gradient is too low to move the bed. However, the perched stream does provide the hydrostatic head for creating a new conduit more nearly aligned with the retreated base level. In this way we can account for the observation that most multi-level caves consist of tiers of passages separated by intervals of non-cavernous rock rather than sequences of continuous deep canyons cut by cave streams maintaining grade with base-leveling surface streams.

It seems likely that the role of sediment transport in cavern genesis and in the development of hydrological systems in karst regions has not been fully appreciated. The sediment flux may turn out to be as important as the groundwater flux in determining the pattern of karst drainage systems.

REFERENCES

Bögli, A. (1960), *Kalklösung and Karrenbildung,* Zeitschr. Geomorphologie Supp. 2, p. 4-21.

——— (1964), *Mischungskorrosion—Ein Beitrag zum Verkarstungsproblem,* Erdkunde, v. 18, p. 83-92.

Bretz, J H. (1942), *Vadose and phreatic features of limestone caverns,* Jour. Geology, v. 50, p. 675-811.

Broughton, P. L. (1972), *Secondary minerals in the cave environment*, Studies Speleology, v. 2, p. 191-207.

Brucker, R. W. (1966), *Truncated cave passages and terminal breakdown in the central Kentucky karst*, Natl. Speleol. Soc. Bull., v. 28, p. 171-178.

Brucker, R. W., Hess, J. W., and White, W. B. (1972), *Role of vertical shafts in the movement of ground water in carbonate aquifers*, Ground Water, v. 10, no. 6, p. 5.

Cullingford, C. H. D. (1953), *British caving*, London, Routledge and Kegan Paul, 468 p.

Curl, R. L. (1958), *A statistical theory of cave entrance evolution*, Natl. Speleol. Soc. Bull., v. 20, p. 9-22.

——— (1960), *Stochastic models of cavern development*, Natl. Speleol. Soc. Bull., v. 22, p. 66-76.

——— (1962), *The aragonite-calcite problem*, Natl. Speleol. Soc. Bull., v. 24, p. 57-73.

——— (1964), *On the definition of a cave*, Natl. Speleol. Soc. Bull., v. 26, p. 1-6.

——— (1965), *Solution kinetics of calcite*, 4th Internatl. Congress Speleol. Proc., Ljubljana, v. III, p. 61-66.

——— (1966), *Caves as a measure of karst*, Jour. Geology, v. 74, p. 798-830.

——— (1966), *Scallops and flutes*, Cave Research Group Great Britain Trans., v. 7, p. 121-160.

——— (1974), *Deducing flow velocity in cave conduits from scallops*, Natl. Speleol. Soc. Bull., v. 36, p. 1-5.

Cvijic, J. (1893), *Das Karstphänomen*, Geog. Abhandlung von A. Penck, v. 5, p. 215-319.

Davies, W. E. (1949), *Features of cavern breakdown*, Natl. Speleol. Soc. Bull., v. 11, p. 34-35.

——— (1951), *Mechanics of cavern breakdown*, Natl. Speleol. Soc. Bull., v. 13, p. 36-43.

——— (1953), *Geology of Pennsylvania caves*, Natl. Speleol. Soc. Bull., v. 15, p. 3-9.

——— (1958), *Caverns of West Virginia*, West Virginia Geol. Survey, v. 19A, 330 p.

——— (1960), *Origin of caves in folded limestone*, Natl. Speleol. Soc. Bull., v. 22, p. 5-18.

Davis, W. M. (1930), *Origin of limestone caverns*, Geol. Soc. America Bull., v. 41, p. 475-628.

DeBellard, E. (1956), *Observaciones espeleologicas*, Acta Cient. Venezolana, v. 7, p. 122-124.

Deike, R. G. (1969), *Relations of jointing to orientation of solution cavities in limestones of central Pennsylvania*, Am. Jour. Sci., v. 267, p. 1230-1248.

Deike, G. H., and White, W. B. (1969), *Sinuosity in limestone solution conduits*, Am. Jour. Sci., v. 267, p. 230-241.

Ewers, R. O. (1966), *Bedding-plane anastomoses and their relation to cavern passages*, Natl. Speleol. Soc. Bull., v. 28, p. 133-140.

Ford, D. C. (1965), *Stream potholes as indicators of erosion phases in limestone caves*, Natl. Speleol. Soc. Bull., v. 27, p. 27-32.

Gardner, J. H. (1935), *Origin and development of limestone caverns*, Geol. Soc. America Bull., v. 46, p. 1255-1274.

Goodchild, M. F., and Ford, D. C. (1971), *Analysis of scallop patterns by simulation under controlled conditions*, Jour. Geol., v. 79, p. 52-62.

Greene, F. C. (1908), *Caves and cave formation of the Mitchell limestone*, Indiana Acad. Sci. Proc., v. 18, p. 175-184.

Groom, G. E., and Coleman, A. (1958), *Speleogenesis of the Dachstein caves*, Cave Research Group Great Britain, Occasional Publ. No. 2.

Grund, A. (1903), *Die Karsthydrographie,* Geog. Abhandlung, v. 7, p. 1-200.

Guilday, J. E., Martin, P. S., and McCrady, A. D. (1964), *New Paris No. 4: A late Pleistocene cave deposit in Bedford County, Pennsylvania*, Natl. Speleol. Soc. Bull., v. 26, p. 121-194.

Halliday, W. R. (1962), *Caves of California*, Privately printed, 194 p.

——— (1963), *Caves of Washington,* Washington Div. Mines and Geology, Inf. Circ. 40, 132 p.

Harmon, R. S., Hess, J. W., Jacobson, R. W., Shuster, E. T., Haygood, C., and White, W. B. (1972), *Chemistry of carbonate denudation in North America*, Cave Research Group Great Britain Trans., v. 14, p. 96-103.

Herak, M., and Stringfield, V. T. (1972), *Karst. Important karst regions of the Northern Hemisphere*, Amsterdam, Elsevier, 551 p.

Hicks, F. L. (1950), *Formation and mineralogy of stalactites and stalagmites*, Natl. Speleol. Soc. Bull., v. 12, p. 63-72.

Hill, C. A. (1976), *Field guide to cave minerals*, Natl. Speleol. Soc., Huntsville, Al, 137 p.

Holland, H. D., Kirsipu, T. V., Huebner, J. S., and Oxburgh, U. M. (1964), *On some aspects of the chemical evolution of cave waters*, Jour. Geology, v. 72, p. 36-67.

Howard A. D. (1963), *The development of karst features,* Natl. Speleol. Soc. Bull., v. 25, p. 45-65.

Jacobson, R. L., and Langmuir, Donald (1970), *The chemical history of some spring waters in carbonate rocks*, Ground Water, v. 8, no. 3, p. 5-9.

Jennings, J. N. (1971), *Karst*, Cambridge, M.I.T. Press, 252 p.

Jones, W. K. (1971), *Characteristics of the underground flood plain,* Natl. Speleol. Soc. Bull., v. 33, p. 105-114.

Kaye, C. A. (1957), *The effect of solvent motion on limestone solution*, Jour. Geology, v. 65, p. 35-46.

Kundert, C. J. (1952), *The origin of the palettes, Lehman Caves National Monument, Baker, Nevada,* Natl. Speleol. Soc. Bull., v. 14, p. 30-33.

Kyrle, G. (1923), *Theoretische Speläologie,* Wien, Österreichischen Staatsdruckerei, 353 p.

Langmuir, Donald (1971), *The geochemistry of some carbonate ground waters in central Pennsylvania,* Geochim. et Cosmochim. Acta, v. 35, p. 1023-1045.

Lattman, L. H. and Parizek, R. R. (1964), *Relationship between fracture traces and the occurrence of ground-water in carbonate rocks,* Jour. Hydrology, v. 2, p. 73-91.

Lehmann, O. (1932), *Die Hydrographie des Karstes,* Leipzig, Franz Deuticke, 212 p.

Martel, E. A. (1921), *Nouveau Traite des Eaux Souterraines,* Paris, Delagrave.

Malott, C. A. (1937), *Invasion theory of cavern development,* Geol. Soc. America Proc., p. 323.

——— (1949), *A stormwater cavern,* Natl. Speleol. Soc. Bull., v. 11, p. 64-68.

——— (1951), *Wyandotte cavern,* Natl. Speleol. Soc. Bull., v. 13, p. 30-35.

Matson, G. C. (1909), *Water resources of the blue grass region, Kentucky,* U. S. Geol. Survey Water-Supply Paper 233, p. 39-46.

Moore, G. W. (1954), *The origin of helictites,* Natl. Speleol. Soc. Occasional Paper no. 1, 16 p.

——— (1962), *The growth of stalactities,* Natl. Speleol. Soc. Bull., v. 24, p. 95-106.

——— (1962), *Role of earth tides in the formation of disc-shaped cave deposits,* 2nd Internatl. Congress Speleol. Proc., v. 1, p. 500-506.

——— (1970), *Checklist of cave minerals,* Natl. Speleol. Soc. News, v. 28, p. 9-10.

Moore, G. W., and Nicholas G. (1964), *Speleology, the study of caves,* Boston, D. C. Heath, 120 p.

Ogden, A., and Ebaugh, W. (1972), *Development of and sedimentation in Milroy Cave,* Nittany Grotto News (Natl. Speleol. Soc.), v. 20, p. 5-22.

Palmer, A. N. (1975), *Origin of Maze Caves,* Natl. Speleol. Soc. Bull., v. 37, p. 57-76.

Parizek, R. R., White, W. B., and Langmuir, Donald (1971), *Hydrogeology and geochemistry of folded and faulted rocks of the central Appalachian type and related land-use problems,* Pennsylvania State University, Earth and Mineral Sci. Expt. Station, Circ. 82, 181 p.

Piper, A. M. (1932), *Ground water in north-central Tennessee,* U. S. Geol. Survey Water-Supply Paper 640, p. 69-89.

Pohl, E. R. (1955), *Vertical shafts in limestone caves,* Natl. Speleol. Soc. Occasional Paper no. 2, 24 p.

Pohl, E. R., and White, W. B. (1965), *Sulfate minerals: their origin in the central Kentucky karst,* Am. Mineralogist, v. 50, p. 1461-1465.

Pluhar, A., and Ford, D. C. (1970), *Dolomite karren of the Niagara Escarpment, Ontario, Canada,* Zeitschr. Geomorphologie, v. 14, p. 392-410.

Rauch, H. W. (1969), *Cave-controlling geologic parameters within the Nittany Valley area of central Pennsylvania,* Natl. Speleol. Soc. Bull., v. 31, p. 40.

Rauch, H. W., and White, W. B. (1970), *Lithologic controls on the development of solution porosity in carbonate aquifers,* Water Resources Research, v. 6, p. 1175-1192.

Shuster, E. T., and White, W. B. (1971), *Seasonal fluctuations in the chemistry of limestone springs: a possible means for characterizing carbonate aquifers.* Jour. Hydrology, v. 14, p. 93-128.

——— (1972), *Source areas and climatic effects in carbonate groundwaters determined by saturation indices and carbon dioxide pressures,* Water Resources Research, v. 8, p. 1067-1073.

Smith, W. O., and Sayre, A. N. (1964), *Turbulence in ground-water flow,* U. S. Geol. Survey, Prof. Paper 402-E, 9 p.

Stone, R. W. (1953), *Descriptions of Pennsylvania's undeveloped caves,* Natl. Speleol. Soc. Bull., v. 15, p. 51-137.

Sweeting, M. M. (1950), *Erosion cycles and limestone caverns in the Ingleborough District,* Geog. Jour., v. 115, p. 63-73.

——— (1972), *Karst landforms,* London, Macmillan, 362 p.

Swinnerton, A. C. (1932), *Origin of limestone caverns,* Geol. Soc. America Bull., v. 43, p. 663-693.

VonKnebel, W. (1906), *Höhlenkunde mit Berücksichtigung der karst phänomene,* Brauschweig, Friedrich Vieweg, 222 p.

Weyl, P. K. (1958), *The solution kinetics of calcite,* Jour. Geology, v. 66, p. 163-176.

White, E. L., and White, W. B. (1968), *Dynamics of sediment transport in limestone caves,* Natl. Speleol. Soc. Bull., v. 30, p. 115-129.

——— (1969), *Processes of cavern breakdown,* Natl. Speleol. Soc. Bull., v. 31, p. 83-96.

White, W. B. (1960), *Terminations of passages in Appalachian caves as evidence for a shallow phreatic origin,* Natl. Speleol. Soc. Bull., v. 22, p. 43-53.

White, W. B., and Deike, G. H. (1962), *Secondary mineralization in Wind Cave, South Dakota,* Natl. Speleol. Soc. Bull., v. 24, p. 74-87.

White, W. B., and Longyear, J. (1962), *Some limitations on speleo-genetic speculation imposed by the hydraulics of groundwater flow in limestone,* Nittany Grotto Newsletter (Natl. Speleol. Soc.), v. 10, p. 155-167.

White, W. B., and White, E. L. (1976), *Base level control of underground drainage in the Potomac River Basin,* Proc. 4th Conf. on Karst Geology and Hydrology (1974), West Va. Geol. and Econ. Survey, p. 41-53.

THE CAVE FAUNA OF PENNSYLVANIA

by
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INTRODUCTION

The first major report on the cave fauna of Pennsylvania was published by Mohr (1932a), but owing to the lack of knowledge of cavernicolous invertebrates at that time, this paper dealt largely with vertebrate animals. Subsequently, extensive biological exploration of Pennsylvania caves was conducted by Kenneth Dearolf and Charles Mohr, and a series of papers on the cave invertebrates were published by Dearolf (1937, 1938, 1941, 1948) as a result of this work. Additional investigations on the vertebrate fauna of Pennsylvania, principally bats and salamanders, were reported by Mohr (1932b, 1932c, 1937, 1942, 1943, 1944, 1945). Mohr (1953) and Frost (1953) also published useful but very general summaries of the information on Pennsylvania cave animals, and these papers were followed a few years later by a short article dealing specifically with the troglobites (i.e., obligatory cavernicoles) of the state by Nicholas (1960a).

In the late spring of 1965 the writer, assisted by John A. Stellmack of The Pennsylvania State University and William Cline of York, Pennsylvania, visited 15 Pennsylvania caves primarily in search of aquatic species. Some of the observations and data collected on this trip are included herein.

The ecological classification of cavernicoles as used by Barr (1968) and Holsinger and Peck (1971) is employed in the following discussion and is defined as follows: (1) *troglobites* - obligatory cave species which are morphologically specialized for, and restricted to, cave habitats and are unable to survive on the surface; (2) *troglophiles* - facultative cave species which frequently inhabit caves and complete their life cycles there but may occupy ecologically suitable habitats on the surface; (3) *trogloxenes* - species which often occur in caves but frequently return to the surface or near the surface (i.e., cave entrance zone) for food; (4) *accidentals* - species which accidentally wander, fall, or are washed into caves and can exist there only temporarily.

The cave fauna of Pennsylvania is characteristically scarce in troglobitic species. Only 15 troglobitic species (including two undescribed forms) are presently known, and less than one-half of them are endemic to this general area. The troglobitic species are taxonomically distributed as follows: planarians (1), isopods (2), amphipods (7), spiders (3), collembolans (1), and beetles (1). Including troglophiles and trogloxenes, however, the total number of species recorded from Pennsylvania caves is much greater than 15. Mohr's 1953 figures of 126 invertebrates and 15 vertebrates were based on the sampling of a little more than 100 Pennsylvania caves and probably represent a fair approximation of the total number of cave-associated species, although continued collecting (especially in the south-central part of the state) might raise this number to some extent.

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INVERTEBRATES

CLASS TURBELLARIA

Three species of planarians or flatworms (order Tricladida) have been recorded from Pennsylvania caves, but only one of them is a troglobite. The troglobitic species, *Sphalloplana (Speophila) pricei* (Hyman), is a member of the family Planariidae, and according to a recent study by Carpenter (1970), its range extends from Pennsylvania south to Virginia and West Virginia and west to Illinois and Missouri. The species is known only from a few caves in the central and southeastern parts of Pennsylvania (Hyman, 1937; Mohr, 1953; Nicholas, 1960a). In Refton Cave, Lancaster County, *S. pricei* occurs on rotting wood and the surface of rocks and is one of the most conspicuous aquatic species in the cave.

The other species of planarians reported from Pennsylvania caves are also members of the family Planariidae and include *Phagocata cavernicola* Hyman and *Phagocata gracilis* (Haldeman). The former species was described from Evac Cave, Westmoreland County by Hyman (1954) but is currently regarded as a probable synonym of *Phagocata morgani* (Stevens and Boring) by Carpenter (1970) and R. Kenk (pers. comm.). *P. gracilis*, like *P. morgani*, is a widely distributed epigean form but has been observed in a number of Pennsylvania caves, including Veiled Lady Cave, Centre County (Dearolf, 1941).

CLASS OLIGOCHAETA

Although often encountered in rotting vegetable debris and organically-rich silt deposits of caves, earthworms have been commonly ignored by biospeleologists. Neither Dearolf (1941) nor Mohr (1953) mentioned earthworms or aquatic oligochaetes from Pennsylvania caves, although the presence of the former group was reported by Gates (1959). This worker reported *Dendrobaena rubida* (Savigny) from Veiled Lady Cave, Centre County, and an undescribed lumbricid species from Dragon Cave, Berks County.

CLASS GASTROPODA

Troglobitic snails are unknown from Pennsylvania caves, but accidental forms have been observed on occasion. Dearolf (1938) reported 12 species of snails from caves in the state but pointed out that nearly all were found dead. Those species found alive had been washed into the caves during spring flooding or had strayed only as far as the crepuscular or twilight zone.

CLASS CRUSTACES

The orders Isopoda and Amphipoda contain nine of the 16 troglobitic species of Pennsylvania, and all but one of them have been described. The order Decapoda (i.e., crayfish) is also represented, but all material collected to date belongs to one or more common epigean species of the genus *Cambarus*. Because of their relative abundance in the groundwaters of the state, the first two orders will be discussed at some length.

Isopoda

Aside from the occasional presence of the epigean "sow bugs" (mostly Oniscidae), the cave isopods of the Pennsylvania are aquatic and belong to the family Asellidae. The terrestrial family Trichoniscidae, represented by a number of troglobites and troglophiles in some of the other cave regions of the country, are unknown from Pennsylvania caves.

One of the most common troglobites in the state is *Asellus pricei* (Levi, 1949), originally described from Refton Cave, Lancaster County, where it occurs in great abundance on rotting wood and debris submerged in the cave lake. This species has been recorded from caves in the Susquehanna and Schuylkill drainage basins of central and southeastern Pennsylvania (caves in Berks, Cumberland, Dauphin, Lancaster, Mifflin, and York Counties) and ranges southward through the eastern part of the Appalachian Valley to the James River basin in Virginia (Holsinger and Steeves, 1971). The Pennsylvania cave records from *Asellus* n. sp. listed by Dearolf (1941) also apply to this species. *A. pricei* is not restricted to caves *per se* but is sometimes found in related groundwater habitats such as springs, seeps, and wells. In cave habitats this species usually occurs in small pools and under gravels and rocks in streams. Another blind, white asellid (*Asellus conestogensis*) was described from Pennsylvania by Levi (1949) and was reported to have been collected from under a stone in Hammer Creek near Buffalo Springs in Lebanon County. This species was recently synonymized with *A. pricei*, however (Holsinger and Steeves, 1971).

A second troglobitic asellid *(Asellus franzi)* was recently described from Pennsylvania by Holsinger and Steeves (1971) and is recorded from Millers Cave in Centre County and Crabtree Cave in Garrett County, Maryland. *Asellus kenki,* described by Bowman (1967), has also been reported from Pennsylvania caves (single cave records from Indiana and Fayette counties), but this species possesses tiny eyes and pigment and is primarily an inhabitant of springs and spring-fed streams.

Dearolf (1937) reported *Asellus richardsonae* (Hay) from Upper and Lower Johnson Cave, Mifflin County, but these records are apparently based on erroneous determinations. The range of *A. richardsonae,* as presently defined, is restricted to caves in the Tennessee River drainage of southwestern Virginia and eastern Tennessee (Steeves, 1963). Similarly, the occurrence of *Caecidotea stygia* Packard (*Asellus stygius*) in caves throughout Pennsylvania as reported by Nicholas (1960a, 1960b) is incorrect. The range of this species is restricted to the subterranean waters of the Interior Low Plateaus of the east-central United States (Steeves, 1963).

Amphipoda

Amphipods of the family Gammaridae are the best represented group of invertebrates in the state in terms of numbers of troglobitic species. To date, species of four different genera have been collected from caves and related groundwater habitats. The most common of the four genera is *Stygonectes* which is represented by five species.

The range of *Stygonectes pizzinii* (Shoemaker), as revised by Holsinger (1967), is more closely circumscribed than previously reported by Shoemaker (1938, 1942), Dearolf (1941), Nicholas (1960a), and Holsinger (1963). This species occurs in the groundwaters of Lancaster and Chester Counties and ranges southward through Maryland to Washington, D.C., and Fairfax County, Virginia. The only cave record for *S. pizzinii* is Refton Cave. The remainder of the locality records are springs, seeps, and wells.

Stygonectes tenuis (Smith), largely an inhabitant of shallow subterranean waters of the Piedmont and Coastal Plain of the eastern United States (two subspecies distributed from southern Connecticut south to Virginia), has been collected from a small stream near the Adams-Franklin county line, where it apparently had been washed from an underground habitat (Holsinger, 1967). Another species of subterranean amphipod, *Stygonectes allegheniensis* Holsinger is closely related to *S. tenuis* and ranges, with only slight geographic variation, from the Piedmont Upland in the vicinity of Lancaster County westward to Garrett County, Maryland, and Fayette County, and then northward (principally through the Appalachian Valley) to central New York State. This species has been collected from caves, wells, seeps, and springs, and apparently has great powers of dispersal as indicated by its wide range and apparent lack of well defined geographic variation. The Pennsylvania cave records for *Synpleonia hayi* Hubricht and Mackin (=*Stygonectes hayi*) published by Dearolf (1941), Hubricht (1943), and Nicholas (1960a, 1960b) also pertain to *S. allegheniensis*. *S. hayi* is authentically known only from its type locality, a spring in Washington, D.C. (Holsinger, 1967).

Two other species of *Stygonectes* are also known from caves in Pennsylvania. *S. stellmacki* Holsinger is an extremely rare form known only from Millers Cave, Centre County, while *S. gracilipes* Holsinger, a more common species, is recorded from Needy Cave, Franklin County. The latter species also ranges southward through the Appalachian Valley to Rockingham County, Virginia (Holsinger, 1969).

The genus *Crangonyx* is represented in Pennsylvania by *C. dearolfi*, a large troglobitic species that was described by Shoemaker (1942) from specimens collected by K. Dearolf from Hobo Cave in Berks County. This species is also known from single caves in Cumberland, Dauphin, and York Counties and ranges southward into Washington County, Maryland (Holsinger, 1969; Franz and Slifer, 1971). The genus *Stygobromus* is also found in Pennsylvania, but to date it is represented by a single collection of an undescribed species from a cave in Franklin County.

Gammarus minus Say, a common widespread species that inhabits springs, spring-runs, and caves of the eastern and southeastern United States, is occasionally encountered in Pennsylvania caves (Dearolf, 1937, 1941; Hubricht, 1943). This species is probably a troglophile, but its association with caves is quite variable throughout its range (Holsinger and Culver, 1970).

Dearolf (1937, 1941, 1948) reported *Synpleonia clantoni* Creaser (=*Stygonectes clantoni*) from caves in Pennsylvania, but these records are based on erroneous determinations, inasmuch as this species is known only from groundwater habitats in eastern Kansas and western Missouri (Holsinger, 1967). Moreover, Nicholas' references (Nicholas, 1960a, 1960b) to *Crangonyx obliquus* (Hubricht and Mackin) as a troglobitic species of Pennsylvania and elsewhere are in error. This species is unknown from cave waters or similar subterranean habitats.

CLASS DIPLOPODA

Troglobitic millipeds constitute an important element of the cave fauna of the central and southern Appalachians and Interior Low Plateaus, but they are not found in Pennsylvania caves. Loomis (1939) described *Conotyla vaga* (=*C. blakei*) (family Conotylidae) from specimens collected by K. Dearolf from caves in Berks, Dauphin, and Mifflin Counties, and more recently this species was recorded from Blair County (Causey, 1960) and Refton Cave, Lancaster County (Holsinger, unpublished data). *Conotyla blakei* (Verhoeff) is a troglophile, and, outside of Pennsylvania, this species is reported from Molers Cave, Jefferson County, West Virginia, caves in Washington County, Maryland, caves and forests in New York State and forests in New England. The distributional pattern and ecology of this species were recently discussed by Shear (1971), who regards the cave populations as relicts which were left behind as the species migrated north following the retreat of the Wisconsin glacier at the end of the Pleistocene.

A number of other milliped species occur in Pennsylvania caves and are either trogloxenes or accidentals. Dearolf (1938) reported *Polydesmus* (*Pseudopolydesmus* in part) and *Scytonotus*; Fowler (1943) listed *Polydesmus*; more recently the writer collected *Brachydesmus*. All three genera belong to Polydesmidae, a family also represented in caves in certain other areas of North America.

CLASS CHILOPODA

Centipedes are rare in Pennsylvania caves (as well as elsewhere) and are usually associated with the crepuscular zone. Members of the family Geophilidae have been collected from several caves in eastern and central Pennsylvania (Dearolf, 1938; Holsinger, unpublished data).

CLASS ARACHNIDA

This arthropod class is represented in Pennsylvania caves by three orders: Araneae (spiders), Acarina (mites), and Opiliones (harvestmen). Only the first order contains troglobitic forms.

The extent and distribution of cave-associated mites is still poorly known, and few of them have been collected from Pennsylvania caves. Dearolf (1941) listed four genera, and the writer (Holsinger, 1965) added a fifth. Cave representatives of the family Parasitidae (*Parasitus* and *Pergamasus*) are apparently free-living and some may be troglophiles, but the remaining genera reported by Dearolf are members of ectoparasitic groups and are trogloxenes or accidentals.

Harvestmen of the genus *Leiobunum* (also called "daddy-long-legs") are occasionally common in large clusters on damp walls near cave entrances (Mohr, 1953, Figure 5) and are trogloxenes. Dearolf (1941) listed *Leiobunum* from three caves, but this genus has also been observed in other caves.

Species of at least five families of spiders are recorded from Pennsylvania caves (Dearolf, 1941), but only three families (Argiopidae, Nesticidae, and Linyphiidae) are frequently encountered and contribute significantly to the cave fauna. One of the most frequently observed spiders is the trogloxenic *Meta menardi* (Latreille), or cave orb weaver, which is often found near cave entrances and for distances up to several hundred feet inside. This species is relatively large, darkly pigmented, and has well-developed eyes. Another trogloxene often observed in caves, but which is somewhat smaller and lighter in color, is *Nesticus pallidus* Emerton. This species has been reported from caves in other states (Barr, 1961; Holsinger, 1964; Holsinger and Peck, 1971; Franz and Slifer, 1971) and has a very wide distribution.

Three species of linyphiid spiders—*Porrhomma cavernicolum* (Keyserling), *Phanetta subterranea* (Emerton), and *Bathyphantes weyeri* (Emerton)—occur in Pennsylvania caves and are considered to be troglobites. Although unknown from epigean or endogenous habitats, these three species have extremely wide ranges for troglobites and are distributed over most of the southeastern United States (Nicholas, 1960b; Holsinger, 1963). The troglobitic linyphiids are typically small, almost colorless, and have reduced eyes. Dearolf (1941) reported *Troglohyphantes incertus* (=*Porrhomma cavernicolum*) from single caves in Mifflin, Berks, and Dauphin Counties, and Fowler (1942) reported this species from Needy Cave, Franklin County. Graham (1966) observed a population of *Bathypantes weyeri* in an excavated sinkhole-cave at New Paris, and W. J. Gertsch (in litt.) has a record for this species from Refton Cave, Lancaster County. *Phanetta subterranea* is known from several caves in the western part of the state (Fayette and Westmoreland Counties), and additional unpublished Pennsylvania cave records for the other troglobitic spiders are established.

CLASS INSECTA

At least four insect orders are commonly encountered in Pennsylvania caves: Collembola (springtails), Orthoptera (crickets), Coleoptera (beetles), and Diptera (flies). Several other orders are also represented but occur much less frequently.

Dearolf (1941) listed *Campodea cookei* Packard (order Diplura, family Campodeidae) from Refton Cave and later pointed out (Dearolf, 1948) that it might be a troglobite. This is apparently an erroneous determination, since to the writer's knowledge, *C. cookei* has remained obscure since its redescription from caves in central Kentucky and southern Indiana by Packard in 1888 (see Condé, 1949). The species from Refton Cave is possibly an undescribed form of the genus *Plusiocampa,* a genus represented by a number of troglobitic species (many undescribed) from the southeastern United States.

Cavernicolous collembolans are usually associated with decaying organic debris or animal droppings and occur from the twilight zone well into the deeper recesses of many caves. Dearolf (1941) listed a number of different genera and species of the families Entomobryidae and Sminthuridae from Pennsylvania caves. On the basis of the revisionary studies of these groups by Christiansen (1960a, 1960b, 1964, 1966), however, many of the names given by Dearolf are apparently incorrect, and the material on which these names was based should be re-examined in light of Christiansen's recent studies.

The majority of the cavernicolous collembolans of Pennsylvania belong to the genera *Tomocerus, Sinella, Onychiurus,* and *Arrhopalites*. Of these four genera, *Tomocerus* appears to be the most common, and most of the cave material pertaining to it belongs to the widespread species (or species complex?) *T. flavescens* (Tullberg) (see Christiansen, 1964, for the distribution of ths species).

Dearolf (1941) listed *Sinella lucifuga* Folsom from single caves in Mifflin and Dauphin Counties, but this species was synonymized with *Sinella cavernarum* (Packard) by Christiansen (1960a). *S. cavernarum* is widely distributed (i.e. reported from caves in Indiana, Kentucky, Tennessee, and Missouri, and a grave in Washington, D.C.) but is nevertheless sometimes regarded as a troglobite (*Christiansen,* in litt.). Dearolf (1941) also reported *Arrhopalites mammouthia* Banks from Veiled Lady Cave, Centre County, but this species was recently synonymized with *Arrhopalites pygmaeus* (Wankel) by Christiansen (1966), the latter being a common troglophile in caves of the southeastern United States.

Two species of cave crickets (order Orthoptera, family Gryllacrididae), *Ceuthophilus gracilipes* (Haldeman) and *Hadenoecus puteanus* (Scudder), are common in Pennsylvania. Both species are trogloxenes and do not penetrate caves much beyond the crepuscular zone. Cave records for these crickets are numerous (see Dearolf, 1937, 1941).

Three species of moths (order Lepidoptera, family Noctuidae) have been observed in Pennsylvania caves, and these include *Scoliopteryx libatrix* Linnaeus, *Hypena humuli* Harris, and *Plathypena scabra* Fabricius (Dearolf, 1937, 1941; Mohr, 1932a, 1953). All three species apparently use caves as hibernacula during the winter and never occur far from the crepuscular zone. Of the three species, *S. libatrix* is the most frequently observed.

Most of the beetles (Coleoptera) found in Pennsylvania caves are either accidentals or trogloxenes. A few, however, like certain species of the families Staphylinidae and Carabidae, are more closely associated with caves, and at least one species of the latter family is a troglobite. In addition to the staphylinids and carabids, Dearolf (1941) reported the following families from Pennsylvania caves: Silphidae (carrion beetles), Scarabaeidae (scarab beetles), Cryptophagidae (silken fungus beetles), Dermestidae (dermestid beetles), and Cantharidae (soldier beetles).

Staphylinid beetles are common in caves in many parts of North America and are usually associated with animal feces or decaying vegetable matter in damp places. All are either trogloxenes or troglophiles. The genus *Quedius* is the most common staphylinid found in caves of the eastern United States, and Dearolf (1941) reported it from 13 caves in eastern and central Pennsylvania.

With the exception of a single, undescribed species of the cave-related genus *Pseudanophthalmus,* the rich troglobitic carabid beetle fauna of the Appalachians and the Interior Low Plateaus does not extend into Pennsylvania. This undescribed species is known only from a single cave population in Fayette County that was first sampled by Dr. Carl Krekeler in 1957. Other carabids, such as *Harpalus* and *Bembidion,* also occur in caves of the state (Dearolf, 1941; Barr, 1964), but they are not common and are probably trogloxenes.

Dipterous insects (flies) are often observed in Pennsylvania caves, but the majority of species do not penetrate far beyond the crepuscular zone. Those groups which occur often enough and deep enough in caves to be considered troglophiles include: fungus gnats of the families Mycetophilidae and Sciaridae; small dung flies of the genus *Leptocera* (Sphaeroceridae); hump-backed flies of the genus *Megaselia* (Phoridae); heleomyzid flies (Heleomyzidae) of the genera *Heleomyza* and *Amoebaleria.* Most of these genera occur either on damp, decaying animal droppings or in rotting vegetable matter. Fungus gnats are often conspicuous in the larval stage, but the remainder are more frequently observed as adults. Some, like *Leptocera* and the heleomyzids, are sometimes represented by rather large populations.

Hibernating flower flies (*Eristalis tenax* Linnaeus, family Syrphidae), mosquitoes (Culicidae), moth flies (Psychodidae), and crane flies (Tipulidae) are occasionally observed near cave entrances in Pennsylvania (Dearolf, 1937, 1941; Mohr, 1953), where they are probably accidental or exist as marginal trogloxenes.

Three other insect orders sometimes, but rarely, encountered in caves of the state include fleas (Siphonaptera), stoneflies (Plecoptera), and true bugs (Hemiptera). All three groups are represented in caves by accidentals. Fleas are transported to caves by their warm-blooded mammal hosts (such as bats and wood rats), and stoneflies, usually in their nymphal or naiad stage, are carried into caves by streams continuous with those on the surface.

VERTEBRATES

Troglobitic vertebrate animals do not occur in Pennsylvania, but a number of trogloxenes, such as salamanders and bats, are found. In view of the detailed discussions of the cave-associated vertebrates of Pennsylvania published by Mohr (1932a, 1932b, 1932c, 1937, 1942, 1943, 1944, 1945, 1953) and to a lesser extent by Dearolf (1956), only a brief summary is necessary at this point.

CLASS OSTEICHTHYES

There are apparently no established records for fishes from Pennsylvania caves. True cave fishes (troglobites) are unknown from the Appalachian Valley and most of the Appalachian Plateau, although accidentals are sometimes observed in cave systems of Virginia, West Virginia, and eastern Tennessee. The northern muddler, *Cottus b. bairdii* Girard (sculpin family Cottidae) is reported from a few caves in the central and southern Appalachians but has not been found in caves as far north as Pennsylvania.

CLASS AMPHIBIA

Six species of the lungless salamanders (family Plethodontidae) have been recorded from caves in Pennsylvania, but with the exceptions of the northern spring salamander, *Gyrinophilus p. porphyriticus* (Green), and the longtailed salamander, *Eurycea l. longicauda* (Green), they are probably accidental. The spring salamander is often abundant in the large stream caves of southwestern Virginia and southern West Virginia but is only occasionally encountered in Pennsylvania caves. The longtailed salamander, on the other hand, is apparently more common in the caves of Maryland and Pennsylvania. Mohr's data on the eggs of *E. l. longicauda* from Ecton Mine in Chester County (Mohr, 1943), the observations of Franz and Slifer (1971) in Maryland caves, and the collection of the larvae of this species from a cave in West Virginia by Hutchison (1956) indicate a rather close association of certain populations with subterranean habitats.

The remaining species of salamanders recorded from Pennsylvania caves include: northern red salamander, *Pseudotriton r. ruber* (Latreille); northern two-lined salamander, *Eurycea b. bislineata* (Green); red-backed salamander, *Plethodon c. cinereus* (Green); and slimy salamander, *Plethodon g. glutinosus* (Green).

Frogs are occasionally observed in or near cave streams, but they are usually found near entrances and are probably accidentals. Mohr (1953) and Dearolf (1956) reported four species of the genus *Rana (pipiens, catesbeiana, clamitans,* and *sylvatica)* from mines and caves in Pennsylvania, but none of these species occurs frequently or in large numbers in cave habitats.

CLASSES REPTILIA AND AVES

Only a few scattered sight records exist for snakes in Pennsylvania caves and these are extremely rare and are based on accidentals found in the twilight zone. Screech owls, barn owls, and phoebes have been recorded from Pennsylvania caves (Mohr, 1953; Dearolf, 1956), but only the last group occurs in caves with any frequency. The nests of the eastern phoebe, *Sayornis phoebe* (Latham), are sometimes found just inside of cave entrances, where they are constructed on rock ledges and in other suitable places.

CLASS MAMMALIA

Although a number of different kinds of mammals have been observed in Pennsylvania caves, only two groups, bats and pack rats, are common. Raccoons and white-footed mice are occasionally seen in caves, but the former are quite elusive and their presence in caves is usually attested to only by tracks and fecal remains. The white-footed mouse, *Peromyscus leucopus noveboracensis* (Fischer), was observed in Pennsylvania caves by Mohr (1953) and Dearolf (1956), but this species is not ordinarily common in caves. Woodchucks, opossums, skunks, foxes, and weasels were also reported from Pennsylvania caves by Dearolf (1956), but these animals are extremely rare in caves and their occurrence is strictly accidental.

Aside from bats, the eastern wood rat or pack rat, *Neotoma floridana magister* Baird, is the most common mammal in Pennsylvania caves. This species is usually restricted to relatively dry areas near entrances or crevices opening to the surface, however. Pack rats also inhabit crevices and fissures in limestone outcrops and cliffs which are situated near creeks and rivers. Some observations on the curious habits of these animals in caves have been described by Mohr (1953), Barr (1961), and Holsinger (1964).

The most conspicuous mammals in Pennsylvania caves are bats, of which six species of the family Vespertilionidae have been reported. Mohr's earlier lists and discussions of Pennsylvania cave bats (Mohr, 1932a, 1953) were thorough and well documented and leave little to be added to at this point. The six species of bats recorded from caves in the state are as follows: big brown bat, *Eptesicus f. fuscus* (Beauvois); little long-eared bat, *Myotis keenii septentrionalis* (Trouessart); little brown bat, *Myotis l. lucifugus* (LeConte); social bat, *Myotis sodalis* Miller and Allen; least bat, *Myotis subulatus leibii* (Audubon and Bachman); and pygmy bat, *Pipistrellus subflavus* (Cuvier).

ZOOGEOGRAPHY

Five conclusions may be reached from an analysis of the cavernicolous fauna of the northern Appalachian region of Pennsylvania.

1. The number of troglobitic species is small in comparison with the number found in the cave regions of the central and southern Appalachians (the Virginias south to Georgia). Several genera which contribute substantially to the diversity of troglobitic species in the central and southern Appalachians are not represented in Pennsylvania caves. Some of these include: *Fontigens* (snails); *Rhagidia* (mites), *Kleptochthonius* and *Apochthonius* (pseudoscorpions); *Pseudotremia* and *Zygonopus* (millipeds); *Caucasonethes* (terrestrial isopods); *Anthrobia* (spiders), and *Pseudosinella* (Collembolans). Moreover, the carabid beetle genus *Pseudanophthalmus*, represented by numerous troglobitic species in karst areas to the south, is known only from one rare species in Pennsylvania.

2. The majority of troglobites (10 species) are aquatic, and four of them (1 isopod and 3 amphipods), while restricted to subterranean habitats, are not found exclusively in caves but inhabit related groundwater habitats (seeps, wells, small springs, etc.) and are sometimes termed phreatobites (see Holsinger, 1967, 1969, for a discussion of this ecological category).

3. With the exception of the beetle *Pseudanophthalmus* sp., the terrestrial troglobites (linyphiid spiders and the collembolan *Sinella cavernarum*) have very wide ranges and are reported from caves throughout much of the southeastern United States. However, *Sinella cavernarum* is a questionable troglobite, and the linyphiid spiders are probably incipient troglobites, presumably derived rather recently from widespread humicolous ancestors.

4. Endemism is very low among Pennsylvania troglobites, and only six of the 15 species are endemic to the general Pennsylvania-Maryland cave region. The remaining species are more widespread, and most of them have ranges which extend south into the central Appalachians of Virginia and West Virginia. Even most of the endemics share close morphological (and genetic?) affinities with species which occur farther south.

5. The number of troglophilic and trogloxenic species is not substantially lower than one finds in other cave areas of the Appalachians, although probably fewer genera and generally smaller populations are represented in these categories in Pennsylvania caves.

Two theories are offered to explain the scarcity of troglobites in the cave region of Pennsylvania. The first theory is based on climatic conditions during periods of Pleistocene glaciation. Although the parts of Pennsylvania with caves were not glaciated during the Pleistocene, the limestone region was nevertheless in proximity to the southern limit of the glaciers at four different times. Therefore, it is assumed that the periglacial climates of this region were marked by prolonged periods of severe cold. The climate was probably so severe that potential troglobite ancestors, such as those postulated by Barr (1968) to have existed during the Pleistocene in suitable habitats in the forested mountains of the southern Appalachians, were forced southward or exterminated. Assuming that some of the more vagile, immediate past ancestors of certain troglobites (such as spiders and collembolans) migrated north again, following retreat of the Wisconsin glacier, and that the periglacial climate of Pennsylvania rendered most caves uninhabitable until well into the Recent, then little time has elapsed for the evolution of a diverse troglobite fauna in the northern Appalachians. This theory accounts in part for the absence of a significant terrestrial troglobite fauna in Pennsylvania and is in line with Vandel's (1964) explanation for similar distributional patterns of terrestrial troglobites in Europe.

The majority of troglobites in Pennsylvania are aquatic species, however, and at least one such species (*Stygonectes allegheniensis*) ranges into the glaciated cave region of New York State. In earlier papers, this writer (Holsinger, 1967, 1969; Holsinger and Steeves, 1971) discussed possible dispersal mechanisms that might be utilized by aquatic troglobites (and phreatobites) but which are presumably unavailable to terrestrial troglobites. Many of the smaller aquatic troglobites are apparently able to travel long distances by interstitial dispersal through superficial groundwaters situated close to the surface. Interstitial dispersal accounts for the distributional patterns of a significant number of amphipods and isopods and may also be applicable to certain species of planarians. Furthermore, it has also been suggested by some workers that certain aquatic forms might have been able to withstand greatly lowered groundwater temperatures during periods of glaciation and therefore could have survived in areas marginal to ice sheets. A number of aquatic troglobites (especially amphipods) inhabit glaciated areas in North America, thus implying that these species or their immediate past ancestors were able to survive periglacial climates near the southern limit of glaciation and then rapidly invade newly opened niches in areas that were freed by retreating ice sheets. In contrast to aquatic troglobites, there are no records for terrestrial troglobites from glaciated areas in either Europe or North America. In addition, terrestrial troglobite faunas are usually impoverished in cave regions lying just south of glaciated areas, especially in regions such as Pennsylvania, which were near glaciation on four different occasions during the Pleistocene.

The second theory offered in explanation of the scarcity of troglobites in Pennsylvania is based on the hypothesis made by Barr (1967, 1968) for the greater species diversity in caves of the Interior Low Plateaus than in caves of the Appalachian Valley. Barr contended that the broadly exposed, relatively undisturbed, highly caverniferous limestone belts of the Mississippian plateau region which extend from southern Indiana to northern Alabama have more extensive, open networks than the limestone areas of the Appalachian Valley. The caverniferous limestones of the latter region are folded and often faulted and are more narrowly delineated because of their restriction to valleys separated by ridges of noncaverniferous, clastic sediments. Cave interconnectivity and open subterranean networks are therefore delimited and often restricted to narrow strike bands which parallel the valleys and ridges. The dispersal potential for cavernicoles would be greater in the Interior Low Plateaus than in the Appalachian Valley, resulting, theoretically, in the evolution of more complex cave communities. Ecologically, species diversity and population stability would be greater in caves with a more complex community structure.

It is possible to apply this theory on a smaller scale and make valid comparisons of species diversity between different cave and karst areas within the Appalachians. As pointed out by Barr (1968), it is highly improbable that troglobites would be found at all in a very small limestone region, while, in contrast, diverse troglobitic fauna may be expected in extensive karst regions which in the geologic past were exposed to climatic instability. In comparison to some of the limestone areas of the Appalachian region in Tennessee, Virginia, and West Virginia (especially the extensive karst areas of the Clinch, Greenbrier and Power River valleys), the limestone areas of Pennsylvania are very narrowly delimited and the caves are typically very small. Presumably, the lack of any significant cave interconnectivity in these areas has greatly limited the dispersal potential of cavernicoles, and the cave communities are quite simple.

The only significant troglobitic fauna in Pennsylvania is composed of aquatic species, some of which are simultaneously phreatobites and most of which do not necessarily depend on cave interconnectivity for dispersal. Moreover, the few terrestrial troglobites which occur there have extensive ranges (with one exception) and probably colonized caves only recently, having been derived from widespread ancestors since the Pleistocene. Combining Barr's theory of cave species diversity with the hypothesis based on the effects of Pleistocene glaciation, the lack of a significant troglobite fauna in the caves of Pennsylvania is not surprising.

REFERENCES

Barr, T. C., Jr. (1961), *Caves of Tennessee,* Tennessee Div. Geology Bull., no. 64, 567 p.

——— (1964), *Non-troglobitic Carabidae (Coleoptera) from caves in the United States,* Coleopterists Bull., v. 18, no. 1, p. 1-4.

——— (1967), *Observations on the ecology of caves,* Am. Naturalist, v. 101, p. 475-492.

——— (1968), *Cave ecology and the evolution of troglobites,* Evolutionary Biology, v. 2, p. 35-102.

Bowman, T. E. (1967), Asellus kenki, *a new isopod crustacean from springs in the eastern United States,* Biol. Soc. Washington, Proc., v. 80, p. 131-140.

Carpenter, J. H. (1970), *Systematics and ecology of cave planarians of the United States,* unpub. Ph.D. thesis, Lexington, Univ. of Kentucky.

Causey, N. B. (1960), *Speciation in North American cave millipeds,* Am. Midland Naturalist, v. 64, no. 1, p. 116-122.

Christiansen, K. A. (1960a), *The genus* Sinella *Brook (Collembola: Entomobryidae) in Nearctic caves,* Annales Entomological Soc. Am., v. 53, no. 4, p. 481-491.

——— (1960b), *The genus* Pseudosinella *(Collembola, Entomobryidae) in caves of the United States,* Psyche, v. 67, no. 1-2, p. 1-25.

——— (1964), *A revision of the Nearctic members of the genus* Tomocerus *(Collembola Entomobryidae),* Rev. Ecol. Biol. Sol. I, v. 4, p. 639-678.

——— (1966), *The genus* Arrhopalites *(Collembola: Sminthuridae) in the United States and Canada,* Internat. Jour. Speleology, v. 2, p. 43-73.

Condé, B. (1949), *Campodéidés cavernicoles de la région des Appalaches,* Notes Biospéologiques, no. 12, p. 125-137.

Dearolf, Kenneth (1937), *Notes on cave invertebrates,* Pennsylvania Acad. Sci. Proc., v. 11, p. 42-47.

——— (1938), *Molluscs and myriapods of some Pennsylvania caves,* Pennsylvania Acad. Sci. Proc., v. 12, p. 64-67.

——— (1941), *The invertebrates of 37 Pennsylvania caves,* Pennsylvania Acad. Sci. Proc., v. 15, p. 170-180.

——— (1948), *An ecological discussion of Pennsylvania's cave invertebrates,* Pennsylvania Acad. Sci. Proc., v. 22, p. 19-22.

——— (1956), *Survey of North American cave vertebrates,* Pennsylvania Acad. Sci. Proc., v. 30, p. 201-210.

Fowler, J. A. (1942), *Cave fauna,* Nat. Speleol. Soc. Bull., v. 4, p. 11-12.

——— (1943), *Cave fauna,* Nat. Speleol. Soc. Bull., v. 5, p. 37-40.

Franz, Richard and Slifer, Dennis (1971), *Caves of Maryland,* Maryland Geol. Survey, Education Ser. no. 3, 120 p.

Frost, S. W. (1953), *Cave insects,* Nat. Speleol. Soc. Bull., v. 15, p. 24-26.

Gates, G. E. (1959), *Earthworms of North American Caves,* Nat. Speleol. Soc. Bull., v. 21, p. 77-84.

Graham, R. E. (1966), *Notes on the New Paris Sink No. 4 fauna, Bedford County, Pennsylvania,* paper presented at Am. Assoc. Adv. Sci. session on cave biology, December 1966, Washington, D.C.

Holsinger, J. R. (1963), *Annotated checklist of the macroscopic troglobites of Virginia with notes on their geographic distribution,* Nat. Speleol. Soc. Bull., v. 25, p. 23-36.

——— (1964), *The biology of Virginia caves,* p. 57-74, in Douglas, H. H., *Caves of Virginia,* Falls Church, Virginia, Econ-Print.

——— (1965), *Free living mites (Acarina) in caves of the eastern United States,* Nat. Speleol. Soc. Bull., v. 27, p. 47-54.

——— (1967), *Systematics, speciation, and distribution of the subterranean amphipod genus* Stygonectes *(Gammaridae),* U. S. Natl. Museum Bull., No. 259, 176 p.

——— (1969), *Biogeography of the freshwater amphipod crustaceans (Gammaridae) of the central and southern Appalachians,* in Holt, P. C. ed., *The distributional history of the biota of the southern Appalachians. Part I: Invertebrates,* Blacksburg, Virginia Polytechnic Institute Press, p. 19-50.

Holsinger, J. R., and Culver D. C. (1970), *Morphological variation in* Gammarus minus *(Say) (Amphipoda, Gammaridae), with emphasis on subterranean forms,* Postilla, no. 146, 24 p.

Holsinger, J. R., and Peck, S. B. (1971), *The invertebrate cave fauna of Georgia,* Nat. Speleol. Soc. Bull., v. 33, p. 23-44.

Holsinger, J. R., and Steeves, H. R., III (1971), *A new species of subterranean isopod crustacean (Asellidae) from the central Appalachians, with remarks on the distribution of other isopods of the region,* Biol. Soc. Washington Proc., v. 84, p. 189-199.

Hubricht, Leslie (1943), *Studies on the nearctic freshwater Amphipoda, III: notes on the freshwater Amphipoda of eastern United States with description of ten new species,* Am. Midland Naturalist, v. 29, p. 683-712.

Hutchison, V. H. (1956), *Notes on the plethodontid salamanders,* Eurycea lucifuga *(Rafinesque) and* Eurycea longicauda longicauda *(Green),* Natl. Speleol. Soc. Occasional Paper, no. 3, 24 p.

Hyman, L. H. (1937), *Studies on the morphology, taxonomy and distribution of North American triclad Turbellaria VIII. Some cave planarians of the United States,* Am. Microscop. Soc. Trans., v. 56, p. 457-477.

——— (1954), *North American triclad Turbellaria XIII. Three new cave planarians,* U. S. Natl. Museum Proc., v. 103, p. 563-573.

Levi, H. W. (1949), *Two new species of cave isopods from Pennsylvania,* Acad. Nat. Sci. Philadelphia, Notulae Naturae, no. 220, p. 1-6.

Loomis, H. F. (1939), *The millipeds collected in Appalachian caves by Mr. Kenneth Dearolf,* Harvard Univ. Mus. Comp. Zoology Bull., v. 86, no. 4, p. 165-193.

Mohr, C. E. (1932a), *Pennsylvania cave fauna,* in Stone, R. E., *Pennsylvania caves,* Pa. Geol. Survey, Gen. Geology Rept. 3, p. 135-143.

——— (1932b), *The seasonal distribution of bats in Pennsylvania,* Pennsylvania Acad. Sci. Proc., v. 6, p. 124-129.

——— (1932c), Myotis subulatus leibii *and* Myotis sodalis *in Pennsylvania,* Jour. Mammalogy, v. 13, p. 160-161.

——— (1937), *Notes on cave vertebrates,* Pennsylvania Acad. Sci. Proc., v. 11, p. 38-42.

——— (1942), *Results of ten years of bat marking in Pennsylvania,* Pennsylvania Acad. Sci. Proc., v. 16, p. 32-36.

——— (1943), *The eggs of the longtailed salamander,* Eurycea longicauda longicauda *(Green),* Pennsylvania Acad. Sci. Proc., v. 17, p. 86.

——— (1944), *A remarkable salamander migration,* Pennsylvania Acad. Sci. Proc., v. 18, p. 51-54.

——— (1945), *Sex ratios of bats in Pennsylvania,* Pennsylvania Acad. Sci. Proc., v. 19, p. 65-69.

——— (1953), *Animals that live in Pennsylvania caves,* Nat. Speleol. Soc. Bull., v. 15, p. 15-23.

Nicholas, Brother G. (1960a), *Troglobites of Pennsylvania,* Netherworld News, v. 8, no. 4, p. 50-53.

——— (1960b), *Checklist of macroscopic troglobitic organisms of the United States,* Am. Midland Naturalist, v. 64, no. 1, p. 123-160.

Shear, W. A. (1971), *The milliped family Conotylidae in North America, with a description of the new family Adritylidae (Diplopoda: Chordeumida).* Harvard Univ. Mus. Comp. Zoology Bull., v. 141, no. 2, p. 55-97.

Shoemaker, C. R. (1938), *A new species of fresh-water amphipod of the genus* Synpleonia, *with remarks on related genera,* Biol. Soc. Washington, Proc., v. 51, p. 137-142.

——— (1942), *Notes on some North American fresh-water amphipod crustaceans and descriptions of a new genus and two new species,* Smithsonian Misc. Collections, v. 101, p. 1-31.

Steeves, H. R., III (1963), *The troglobitic asellids of the United States: the* Stygius *group,* Am. Midland Naturalist, v. 69, no. 2, p. 470-481.

Vandel, A. (1964), *Biospéologie: La Biologie des Animaux Cavernicoles,* Paris, Gauthier-Villars, 619 p.

APPALACHIAN BONE CAVES

by
John E. Guilday*

Whatever else they may contain, caves hold history. From the moment of their inception, or rather, when those processes that form the primary cave cease to operate, erosional and depositional forces that will eventually destroy the cave begin to work. As soon as any direct contact is made with the surface, caves become dumping grounds for surface materials that may eventually choke them. They may also act as biological traps. As a result, a cave floor is often a stratified deposit of surface materials, including animal and plant remains, that can remain untouched for millions of years. The contents, preserved from destructive weather changes, chemical disintegration, or mechanical disturbance, are literally entombed. Such cave deposits, augmented by a few other sources, primarily bog and lake deposits, constitute the primary sources of information about the paleontological history of Appalachia during the Pleistocene period. The past one to two million years was a period of extreme climatic fluctuation associated with four major glacial ice advances over parts of North America. The land forms and climate which are present today represent the modifications made by the last glacial event about 10,000 years ago.

The Appalachian Mountains are extremely old. Presumably, they have been above sea level since Triassic time (200 million years). As a result, erosion has long since wiped out nearly all evidence of life in this area during the latter half of the Mesozoic (age of dinosaurs) and all of the Tertiary (that period which saw the dominance of mammalian life). If such evidence exists it must be buried in such inaccessible places as the Mississippi Delta or far out under the Atlantic Ocean. The Pleistocene with its multiple glaciations culminated in the last and most severe, the so-called Wisconsin glaciation. This vast continental blanket covered most of northern North America with an ice sheet several miles in thickness that extended as far south as present New York City in the East. In the central lowlands west of the Appalachians the ice thrust southward to a point somewhat north of the Ohio River, which roughly delineates its southern border. Portions of extreme northeastern and northwestern Pennsylvania were covered by the ice sheet, and deposits of transported sands and gravels mark its southern boundary in those areas. The Appalachians themselves, from

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Pennsylvania to the south, escaped continental glaciation. There is, however, geological evidence, in the form of boulder fields and ring patterns, that frost action and alpine conditions occurred far south of the continental glacial boundary. This is dramatically echoed by finds of tundra animals in Pennsylvania caves and is still faintly suggested today by the occurrence in the southern Appalachians of enclaves of plants and animals cut off from their present northern ranges by stretches of the mid-Appalachians that are now too warm to support them.

In some areas of the world, Hungary, Poland, Czechoslovakia, Belgium, caves and sinkholes may produce remains of animal life from the Tertiary, or even the Mesozoic (a herd of over 20 large dinosaurs, *Iguanodon,* was discovered in a lower Cretaceous fissure-fill by Belgian coal miners). The geological history of the caves of the Appalachian region, however, appears to extend no further back in time than to mid or possibly early Pleistocene, or if it does, such sites have yet to be discovered. In areas north of the Wisconsin glaciation, the disrupted drainage patterns caused by the extensive and erratic dumping of sand and gravel by the glaciers produced ponds and lakes, often by the hundreds. In time these open bodies of water filled in with stream-transported sediments and vegetation and many such sites today are bogs, which hold unique stratified layers of plant pollen that catalogue in some detail the vegetational sequence of the past 10,000 to 15,000 years. Such bogs occasionally produce bones of mired animals which lived during those early days of ice recession—mastodon *(Mammut),* mammoth *(Mammuthus),* giant beaver *(Castoroides),* extinct musk-ox *(Symbos),* extinct moose *(Cervalces),* and some that live today, such as the caribou (*Rangifer*). South of the continental glacial border such bog deposits are rare, and our main source of information of the life and climate of Appalachia during the Pleistocene lies in the discovery and interpretation of cave deposits.

To be preserved, animal remains must be protected soon after death occurs. This can be accomplished by many methods. Direct preservation, freezing or pickling—such as the frozen remains of woolly mammoth in northern permafrosts or the unique woolly rhinocerous pickled in salt brine since the Ice Age and now stuffed and on exhibition in the Museum of Krakow, Poland—is unknown from the Appalachians. Rapid burial in aggrading water deposits or bogs is not common in mountainous areas. Aside from mastodon remains in Allegheny, Crawford, Huntingdon, and Monroe Counties, Pennsylvania, bog deposits are not very productive paleontological sites. They are, however, very important to the palynologist (the student of fossil plant pollens) and pollen analyses of cores taken from sites such as Pymatuning Swamp, Crawford County, Bear Meadows, Centre County, Marsh (near

Philadelphia) (Martin, 1958), and Glade Run Bog, Somerset County, in Pennsylvania, and Cranesville Swamp, Maryland, and Cranberry Glades, West Virginia, are major sources of paleo-botanical information. Alluvial deposits are likewise scarce. Due to the sorting and abrading effects of stream transport, most bone finds consist of isolated and broken elements of large mammals. Big Bone Lick, Kentucky (Schultz and others, 1963) and Saltville, Virginia (Ray and others, 1967) are good examples of local stream deposits centered around salt accumulations which probably served to attract large herbivores as salt blocks attract cattle today.

By far the bulk of our knowledge of the Appalachian Pleistocene is derived from cave deposits. Caves, fortunately, are scattered in number throughout the mid and southern Appalachians and on their flanks. Cave deposits are unique in several ways. Bone preservation in many instances may be literally perfect, although crushing may occur due to settling of sediments or local stream action. Such deposits are built up by accumulations at the bottom of precipitous well-like sinkholes or by the action of predators, especially cave-inhabiting owls that regurgitate the bones of their prey at their roosts. Occasionally an animal might simply become lost deep in a passage and die. The result in the two former cases affords large collections, sometimes stratified (therefore with a known time sequence), of small mammals—rats, mice, shrews, squirrels, etc., as well as some of the larger forms that may have become trapped or actually lived in the caves. This gives us a glimpse of a large cross section of the animal life at that time (Figures 23, 24 and 25).

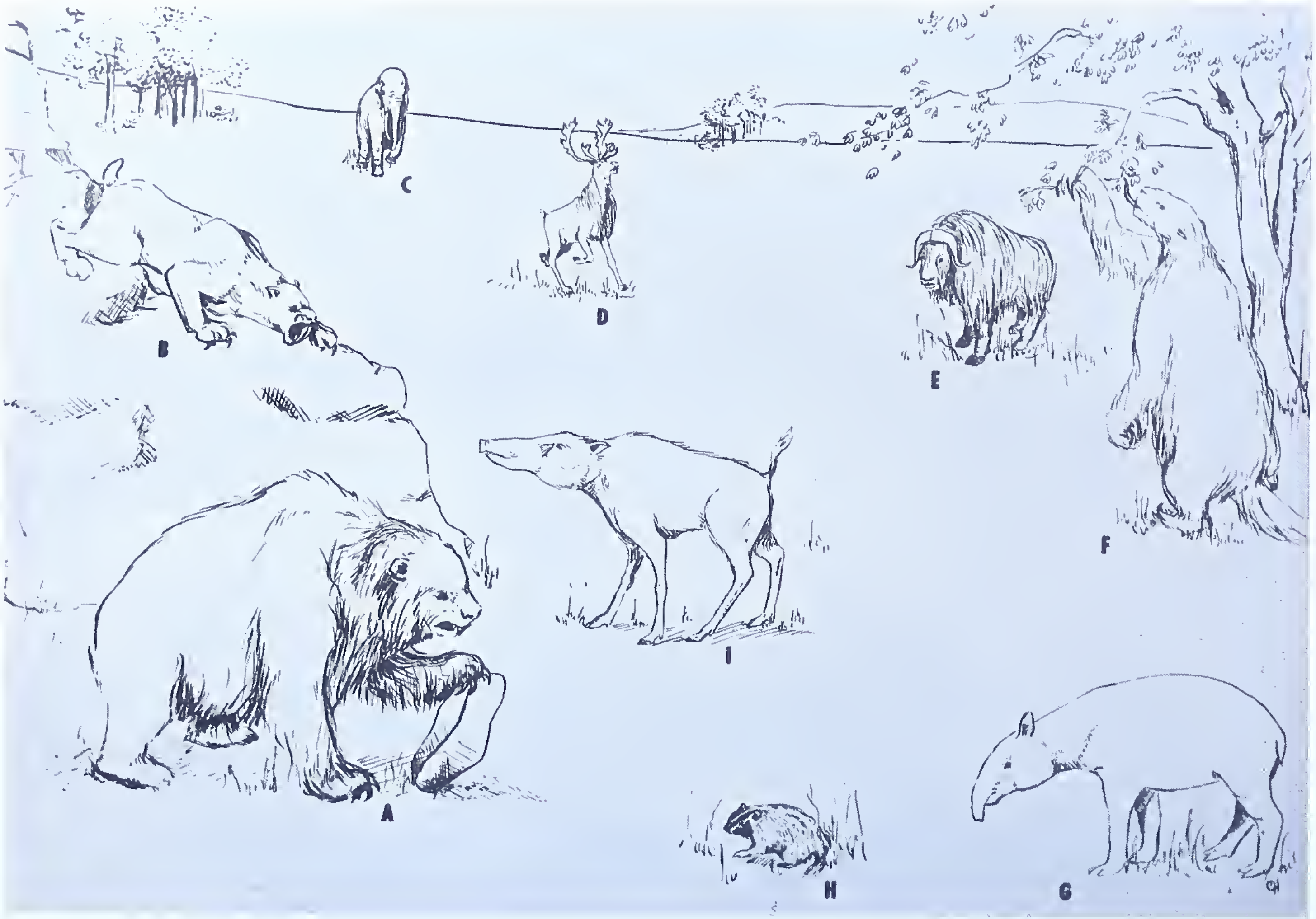
Cave sediments have one distinct disadvantage not shared by stream and lake deposits in that they cannot be correlated with one another by geologic means with the same assurance as can stratified water-lain deposits (this will eventually become possible in sites that have a large enough collection of small mammals by correlating percentages of the various species present, but Appalachian cave paleontology has a way to go before this can be pursued with any assurance). Water-lain deposits, on the other hand, often produce fauna of mixed origin. In other words, there is no guarantee that the animal remains found together in such a deposit in death actually belonged to animals that occurred together in life. Remains could have been transported from many diverse habitats anywhere upstream in the watershed. Cave deposits acting as traps or repositories of carnivore trash of local origin almost surely contain faunal remains from the nearby vicinity. There may be exceptions to this, of course. Climatic change and altitude, both of which affect animal distribution today, played a part and, undoubtedly, a much larger part in governing animal distributions during the Pleistocene when climatic regimes were harsher and subject to greater oscillations.

Although we will consider primarily the cave deposits of Pennsylvania, any discussion of climatic and biological changes associated with time must, of necessity, include sites outside the state. This must be so not only because of the shortcomings of the fossil record, but also because such changes occur over broad areas. Although a good many sites are known and have been studied, they are scattered with no regard to political boundaries even though they may have direct application to the study of Pennsylvania's early prehistory.

The recent rise in the popularity of spelunking has resulted in heightened interest in cave paleontology. New sites have been discovered. The dedication of innumerable volunteers from the ranks of speleology and the financial support of such agencies as the National Science Foundation and the A. W. Mellon Educational and Charitable Trust have resulted in a vast increase in the amount of material available for study. Thanks to the application of the newer research tools such as carbon-14 dating and spectroscopic analyses and the newer concepts of sedimentology, ecology and taxonomy, our knowledge of the Pleistocene period in eastern North America has changed from the scattered facts floating about loosely in time and location, to a discernible, though out of focus, chronological outline of the drastic events that occurred up and down the Appalachians as well as in other parts of the world during the past Ice Age.

Appalachian cave fauna can be roughly divided into three categories. This is so not because there are clear-cut differences between the climatic periods they represent, but because intermediate fauna have yet to be discovered: Recent (roughly from 7,000 B.C. to the present); Late Pleistocene (20,000 years ago to 7,000 B.C.); mid-Pleistocene, possible Illinoian glaciation, as a guess (older than 50,000 to 100,000 years ago).

Probably the oldest Appalachian cave fossil fauna, consisting of extremely shattered and fragmentary remains of bird, mammal, and reptile bones and preserved remains of vegetation, was the famous Port Kennedy Cave deposit at Port Kennedy on the Schuylkill River in Montgomery County, Pennsylvania. It was excavated from the 1870's to the 1890's under the direction of Professor Edward Drinker Cope of Philadelphia (see Hay, 1923, p. 311-320, for a description of the site and the excavations). Much of the material is now lost, but those specimens that did survive are preserved in the Cope Collection at the American Museum of Natural History in New York. Despite the fragmentary condition of the remains, possibly due to stream churning which reduced most of the material literally to a paste (only the teeth survived in their original condition), Port Kennedy Cave produced an astonishing number of specimens: at least 95 giant ground sloth (*Megalonyx*), 11 saber-tooth tiger (*Smilodon*), 25 cave bear (*Arctodus*), 20 peccary (*Mylohyus*), 7 deer (*Odocoileus*), 20 mastodon (*Mammut*), 3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squirrel (*Sciurus*), 1 beaver (*Castor*), 9 horse (*Equus*), 36 tapir (*Tapirus*), round-tailed muskrat (*Neofiber*), extinct pygmy muskrat (*Ondatra*), 7 porcupine (*Erethizon*), 56 rabbit (*Lepus*), 1 mole (*Scalopus*), 8 black bear (*Ursus*), 4 wolverine (*Gulo*), 1 badger (*Taxidea*), 10 coyote and wolf (*Canis*), 3 mountain lions (*Felis*), 4 bobcat or lynx (*Lynx*), and 20 extinct short-faced skunk (*Brachyprotoma*). (Complete faunal lists may be found in major references cited.) Unfortunately, the cave produced very little in the way of small mammal remains. Equally unfortunate was the fact that it was excavated during the pioneering stage of paleontology, when many of the modern concepts of animal taxonomy and distribution were still in their infancy. Because of this, portions of the final report on the fauna by Dr. Cope (1899) are out of date to the point of being misleading. This is so because our knowledge of modern plant and animal distribution and knowledge of the range of variation in modern animal populations was not available a century ago when study collections were smaller or nonexistent. Workers had to do the best they could with what they had. Often minor variants were described as "extinct species." As a result many of the older studies, such as those of the Port Kennedy vertebrates, cannot be correlated with research being conducted today without restudying the original specimens in the light of present knowledge. It is impossible, for instance, at the present writing to even list the number of species of mammals from Port Kennedy Cave. For example, four species of giant ground sloths *(Megalonyx wheatleyi, M. tortulus, M. loxodon, M. scalper),* three "species" of peccaries *(Mylohyus),* even four species of skunks *(Mephitis),* were described from the cave, all based on variations in size and proportions that we now suspect to be individual variants. Were there indeed four different sloths or could the variation be ascribed to growth stages or sex?

Port Kennedy is probably the oldest assemblage of plants and animals known from an Appalachian cave. The fauna show distinct evidence of a greater mixture than exists today—western elements such

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Figure 23. Large mammals of Pennsylvania's Ice Age.
A. Short-faced cave bear, *Arctodus pristinus**; B. Sabertooth tiger, *Smilodon,* ? species*; C. Mastodon, *Mammut americanum**; D. Caribou, *Rangifer tarandus*; E. Extinct "musk-ox," *Symbos cavifrons**; F. Jefferson's ground sloth, *Megalonyx jeffersonii**; G. Tapir, *Tapirus,* ? species*; H. Badger, *Taxidea taxus*; I. Long-nosed peccary, *Mylohyus nasutus**
* extinct.

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as the badger and the coyote, northern elements such as the wolverine, and animals of southern origin, although not necessarily indicative of a warm climate, such as the tapir. This is the only eastern site to produce remains of the saber-tooth tiger, although it is believed to have survived as late as 15,000 years ago, based upon carbon-14 dating at Rancho La Brea, California. These cave fauna are in the process of being restudied by specialists working with particular groups of animals, and it may be years before the full scientific value of the collection will be realized. It was not until a few years ago, for instance, that an extinct form of the round-tailed muskrat *(Neofiber)*, an animal now confined to Florida, was identified from the Port Kennedy collection (Hibbard, 1955).

Roughly contemporaneous is the collection from Cumberland Bone Cave, Allegany County, Maryland (Gidley and Gazin, 1938). It was

Roughly contemporaneous is the collection from Cumberland Bone Cave, Allegheny County, Maryland (Gidley and Gazin, 1938). It was originally excavated in 1912 by the United States National Museum, where the bulk of the specimens now reside. Additional explorations were conducted by Princeton University, Brother G. Nicholas (1953) (specimens now at Carnegie Museum), and at the present writing by Carnegie Museum. As at Port Kennedy, a large number of large mammal remains were discovered. This time, fortunately, they were in excellent condition, although often badly encased in flowstone, making preparation difficult. Large plant-eaters were abundant, shrub ox *(Euceratherium)*, peccaries *(Platygonus* and *Mylohyus)*, deer *(Odocoileus)*, tapir *(Tapirus)*, horse *(Equus)*, mastodon *(Mammut)*, and giant ground sloth *(Megalonyx)*. Carnivores included jaguar *(Panthera)*, mountain lion *(Felis inexpectata)*, cave bear *(Arctodus)*, black bear *(Ursus vitabilis)*, a pack of wolves *(Canis armbrusteri)*, coyote *(Canis priscolatrans)*, badger *(Taxidea)*, spotted skunk *(Spilogale)*, short-faced skunk *(Brachyprotoma)*, wolverine *(Gulo)*, otter *(Lutra)*, mink *(Mustela)*, fisher *(Martes)*. Smaller mammals included a shrew, 2 species of bats, 3 species of mice, pygmy muskrat

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Figure 24. Small mammals of Pennsylvania's Ice Age.
A. Thirteen-lined ground squirrel, *Spermophilus tridecemlineatus;* B. Red squirrel, *Tamiascuriurus hudsonicus;* C. Snowshoe hare, *Lepus americanus;* D. Cony, *Ochotona,* ? species; E. Arctic shrew, *Sorex arcticus;* F. Collared lemming, *Dicrostonyx hudsonius;* G. Yellow-cheeked vole, *Microtus xanthognathus;* H. Pocket gopher, *Plesiothomomys potomacensis**
* extinct.

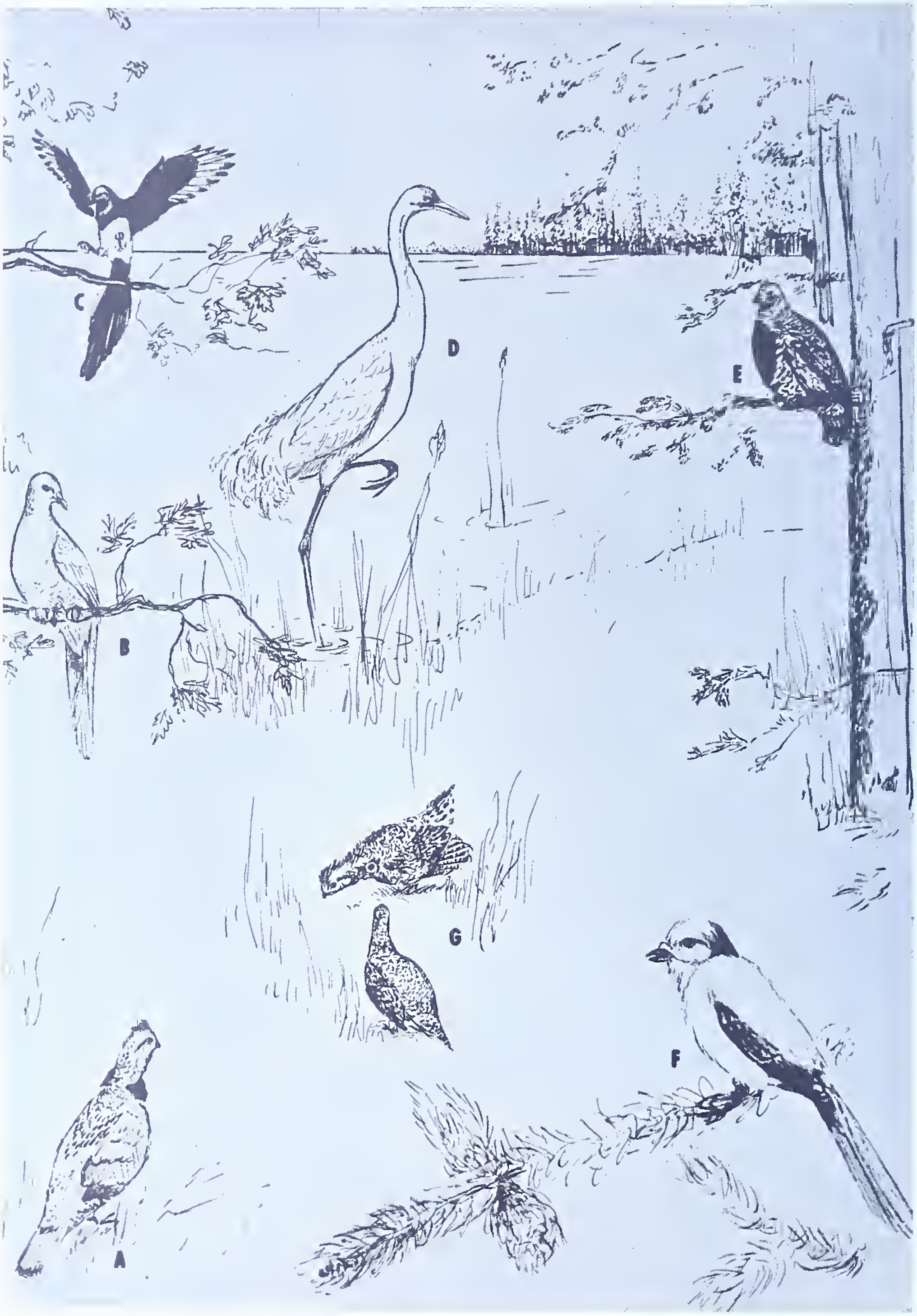

Figure 25. Birds of Pennsylvania's Ice Age
A. Ruffed grouse, *Bonasa umbellus;* B. Passenger pigeon, *Ectopistes migratorius*;* C. Magpie, *Pica pica;* D. Whooping crane, *Grus americana;* E. Spruce grouse, *Canachites canadensis;* F. Canada jay, *Perisoreus canadensis;* G. Sharp-tailed grouse, *Pedioecetes phasianellus*
* extinct.

(Ondatra annectens), gopher *(Plesiothomomys),* ground squirrel *(Spermophilus),* snowshoe hare *(Lepus americanus),* and the pica *(Ochotona),* a hamster-sized, rabbit-like animal now confined to western North America in rocky areas. In an effort to obtain remains of additional small mammals, recent work by Carnegie Museum has proved extremely productive. Among rodents, the extinct beaver-like animal *Paradipoides,* known from Illinoian deposits in the Great Plains, was represented by a single molar tooth which appeared in the screenings of the deposit only last year. Literally thousands of small mammal teeth, primarily those of microtine rodents, including as at Port Kennedy the extinct Pleistocene muskrat *(Ondatra),* have been recovered but have not been adequately studied. Several teeth believed to be those of the tiny extinct mouse, *Atopomys,* described and known only from isolated molars from a fissure fill, Austin, Texas (Patton, 1965), have been recovered. Two woodrats are represented: the commonest, *Neotoma,* which still occurs in the Appalachians, and a rarer, larger, extinct woodrat, *Parahodomys,* known only from lower jaws. A large chipmunk-size extinct species of deer mouse, *Peromyscus cumberlandensis,* was described from teeth and jaw fragments from Cumberland Cave in 1967 (Guilday and Handley, 1967). Since that time it has turned up in excavations at Trout Cave, West Virginia, and Ladd's Quarry, Georgia (Ray, 1967), and was apparently a distinctive and widespread inhabitant of the Appalachians at one time. A restudy of the "extinct" bat of the site, *Eptesicus grandis,* characterized mainly by greater size, has shown that it can be matched in size by some geographic populations of the living big brown bat, *Eptesicus fuscus,* and it is not a valid fossil form (Guilday, 1967a). Restudy of the "crocodile" tooth reported from this site (Gidley and Gazin, 1938, p. 10) established that it was in reality an unerupted bear canine (Richmond, 1963). This removed a climatic oddball from an otherwise temperate or cool-weather fauna. Cumberland Cave, as was Port Kennedy, is characterized by a mixture of animals that do not occur together at the present time, as well as a high percentage of extinct large mammals.

Frankstown Cave, at Hollidaysburg, Blair County, Pennsylvania, was excavated by O. A. Peterson of Carnegie Museum (1926). Its chronological position is enigmatic, but is probably, at least in part, pre-Wisconsin. Forest musk-ox *(Bootherium),* giant cave bear *(Arctodus),* giant ground sloth *(Megalonyx),* mastodon *(Mammut),* the extinct moose *(Cervalces),* the extinct elk-like deer (*Sangamona,* originally identified as western mule deer) were present, as well as snowshoe hare *(Lepus americanus)* and red-backed vole *(Clethrionomys).* Unfortunately, much of the material was broken and dispersed by quarry workmen, and Peterson could do little more than salvage the pieces. The site is now covered by U.S. Route 22.

These are perhaps our earliest glimpses of the Appalachian Mountain fauna. It proves to be quite a different world than that of today, where mastodons, the large carnivorous cave bears, saber-tooth tigers, horses, buffalo-sized musk-oxen, moose, tapirs, jaguars, and peccaries roamed the Pennsylvania countryside in addition to the modern elk, deer, wolf, mountain lion, and black bear, the only large mammals to have survived from prehistoric times.

One other site gives us a partial glimpse into these early days and serves as a bridge leading up to later Pleistocene times. A 12-foot excavation of Trout Cave, Pendleton County, West Virginia, by a Carnegie Museum field party, produced a stratified, but frustratingly fragmentary, collection of small mammal teeth and large mammal bone and teeth fragments. In the lower levels were found such pre-Wisconsin indicators as cony *(Ochotona),* round-tailed muskrat *(Neofiber),* pygmy muskrat *(Ondatra annectens),* and pocket gopher *(Plesiothomomys),* plus a primitive and as yet unidentified species (perhaps new to science) of field vole *(Microtus).* These forms do not appear in the upper levels of Trout Cave, but other small mammals characteristic of late Pleistocene and modern times do. Although it seems to present a transition, there is no way of dating the site at the present time or of determining how long it took for the deposition to accumulate. Perhaps someday we will be in a better position to answer some of these questions.

The second major time horizon, that of the late Pleistocene, is represented in some detail by the deposits of New Paris Sinkhole No. 4, Bedford County, Pennsylvania. Excavations carried out by Carnegie Museum and the National Speleological Society in the early 1960's (Guilday and others, 1964) produced a 30-foot stratified deposit of over 3,000 vertebrates, most of them squirrel size or smaller. All were, with a few minor exceptions, characteristic of the sub-Arctic, such as yellow-cheeked vole *(Microtus xanthognathus)* (see map, Figure 26), spruce vole *(Phenacomys),* northern bog lemming *(Synaptomys borealis),* arctic shrew *(Sorex arcticus),* water shrew *(S. palustris),* and pygmy shrew *(Microsorex).* This site produced the first North American fossil record of the collared lemming *(Dicrostonyx),* a mammal confined to and adapted for the tundra environment of northern Canada and Alaska. Collared lemming remains have since been recovered from Pleistocene sites in the Rocky Mountains, Jaguar Cave, Idaho (Guilday and Adam, 1967), and Little Box Elder Cave, Wyoming (Anderson, 1968). The carbon-14 date of 11,000 ± 1,000 BP (before present) at the New Paris site is roughly concordant with the 11,580 ± 250 BP carbon-14 date at Jaguar Cave, and lemming remains at these sites, especially because they are found associated with other cold weather vertebrates, must indicate former tundra conditions. With the

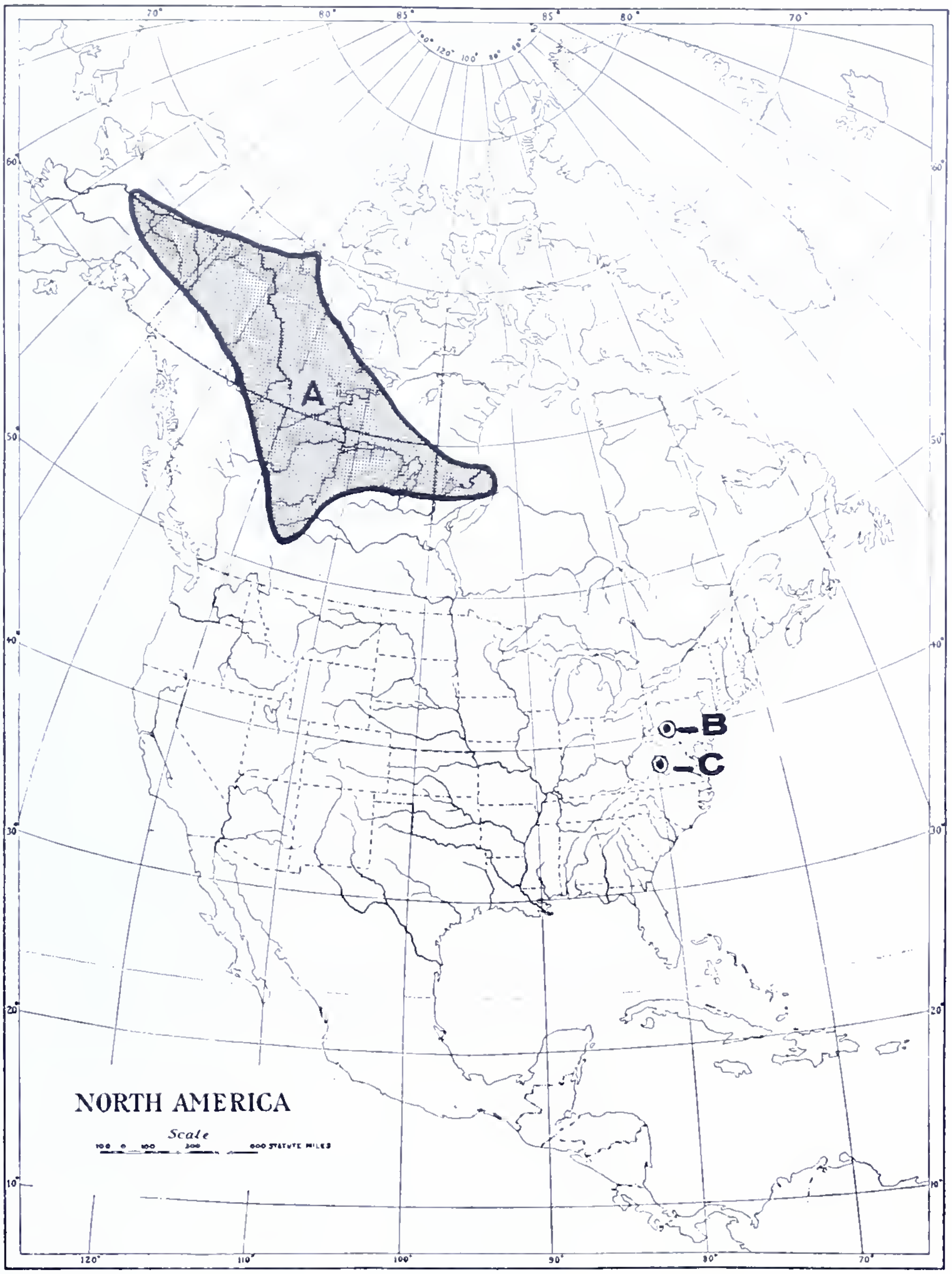

Figure 26. A. Modern range of yellow-cheeked vole, *Microtus xanthognathus;* B. New Paris No. 4, Pa.; C. Natural Chimneys, Va.
(Both cave sites yielding bones of yellow-cheeked vole.)

exception of the extinct long-nosed peccary (that heretofore had not been known to have survived to such a late date), the bulk of the New Paris collection was composed of small mammal remains. This makes it difficult to correlate with earlier cave collections in which remains of large mammals predominated. A distinct continental element occurs in the fauna of this period—the 13-lined ground squirrel *(Spermophilus)* and sharp-tailed grouse *(Pedioecetes)*. These mid-western elements, as well as the western magpie *(Pica)*, have been traced as far south and east as Natural Chimneys, Augusta County, Virginia (Guilday, 1962), in association with such northern forms as spruce grouse *(Canachites)*, Canada jay *(Perisoreus)*, yellow-cheeked vole *(Microtus xanthognathus)*, and spruce vole *(Phenacomys)*. An isolated molar of the giant beaver *(Castoroides)* from this site may be of an earlier date, but it is well established that this bear-sized rodent did survive the last glaciation, as it is commonly found in bog remnants of post-Wisconsin lakes in glaciated areas. Natural Chimneys also produced remains of additional species of birds including the whooping crane *(Grus americana)* and passenger pigeon *(Ectopistes)*, the former no longer found in Virginia, the latter extinct (Wetmore, 1962). Grizzly bear *(Ursus arctos)* teeth of unknown age, but presumably of this time period, are known from Organ Cave, Greenbrier County, West Virginia. Western forms mixed with typical eastern species have also been found in Kentucky—Savage Cave, Logan County, gopher *(Geomys)*, Welsh Cave, Woodford County, grizzly bear *(U. arctos)* (Guilday, 1968), badger *(Taxidea)*, 13-lined ground squirrel *(Spermophilus)*, gopher *(Geomys)*; and Robinson Cave, Overton County, Tennessee (Guilday and others, 1969), 13-lined ground squirrel. The carbon-14 date associated with the Welsh Cave fauna, 12,950 ± 550 BP, places it in early postglacial times, somewhat earlier than that of New Paris No. 4, Pennsylvania, but all of these sites seem to be associated with an open semi-prairie, semi-forest situation, perhaps more marked towards the north immediately following the final retreat of glacial ice, enabling nominally western species, i.e. those adapted for a grasslands or an open country/forest edge environment, to penetrate into the east before ameliorating climate allowed deciduous forest advance to the north.

Recent discoveries at Bootlegger Sink, York County, Pennsylvania (Guilday and others, 1966), have established the presence of the typical late Pleistocene "northern-western" fauna in that area, yellow-cheeked vole *(M. xanthognathus)*, northern bog lemming *(Synaptomys borealis)*, spruce vole *(Phenacomys)*, arctic shrew *(Sorex arcticus)*, 13-lined ground squirrel *(Spermophilus)*, all of which occurred at New Paris No. 4, Pennsylvania, and Natural Chimneys, Virginia, and caribou *(Rangifer)*. Caribou remains have also been recovered from Hartman's Cave, Monroe County and Durham Cave, Bucks County

(Leidy, 1889), Pennsylvania, and as far south as Saltville, Virginia (Ray and others, 1967) and Big Bone Lick, Kentucky (Schultz and others, 1963).

A site somewhat later in time, but crucial as a time marker, is Hosterman's Pit, Centre County, Pennsylvania (Guilday, 1967b). Here a small collection of Recent, but prehistoric, mammals including elk was found, all of which occur in the area today. Charcoal, associated with the remains and believed to be of forest fire origin, was found in talus from a now clogged roof opening. Carbon-14 analysis of the charcoal gives a date of 9,240 ± 1,000 BP. Knowing that the 11,300 year old fauna of New Paris No. 4 was still of a distinctly boreal type, composed primarily of mammals whose preferred habitat today centers at a latitude some ten degrees farther north in central Canada and that by about 9,000 years ago a modern fauna and, by inference, modern vegetation and climate essentially as we know it today, had replaced this earlier biota, we can bracket the climatic changeover between 11,000 and 9,000 years ago, a time point corroborated by pollen profiles of bogs in the southern portions of the glaciated areas.

The third time period represented in Appalachian cave deposits is the Recent. Most, but not all, bones found in a state of good preservation lying on cave floors will be of relatively recent origin. There are enough exceptions, however, such as the skeleton of the extinct Florida spectacled bear *(Tremarctos floridanus)* from Grassy Cove Saltpeter Cave, Tennessee (Guilday and Irving, 1967), and several jaguar skeletons, including muddy paw prints (Simpson, 1941), to excite the imagination. Bones lying on the surface may have been eroded out of other deposits such as the giant cave bear from Grapevine Cave, West Virginia or the armadillo remains from Organ-Hedricks Cave, West Virginia (Guilday and McCrady, 1966). Bones of the giant ground sloth *(Megalonyx)* from Big Bone Cave, Van Buren County, Tennessee, still retained dried ligament, periosteum, and the horny claw (Barr, 1961). All finds, therefore, should be carefully studied before any judgment is made as to their age or importance.

Probably the earliest attempt in Appalachian paleontology was made by Thomas Jefferson (he coined the name *Megalonyx,* meaning "big claw"). It must have been stimulating to live in an age when one could speculate as to the possible existence of as yet undiscovered animals in the American hinterlands. Jefferson expressly instructed Lewis and Clark to keep an eye open for mastodons during their trek to the Pacific. Jefferson tentatively identified the giant ground sloth remains from Organ Cave, West Virginia, as those of a huge lion-like animal and speculated, "In the present interior of our continent there is surely space and range enough for elephants and lions, if in that climate they could subsist; and for mammoths and megalonyses who may subsist there. Our entire ignorance of the immense country to the West and Northwest, and of its contents, does not authorise us to say what it does not contain" (Jefferson, 1797).

Some of the earliest concerted Pennsylvania cave excavations were carried out by S. F. Baird, who eventually became one of America's foremost zoologists. Perhaps because of this association with Baird, these early cave collections have been given greater notoriety than they deserve. Study has shown that they are all bones of Recent mammals (Miller, 1940). One "extinct" Pennsylvania mammal, described from skeletal remains from "caves near Carlisle" in 1857 by Baird, has since proved to be quite lively today—the Appalachian cave rat *(Neotoma floridana)*. Thirty-six years later it was discovered alive in Lewis' Cave Rocks, Cumberland County, Pennsylvania, and described by Witmer Stone as *Neotoma pennsylvanica* (Rhodes, 1903). It was since discovered to be synonymous with the southern woodrat, *Neotoma floridana,* and the specific name *pennsylvanica* is no longer used.

The phrase "heritage of the hills" may sound a bit corny in this day and age, but it is there and waiting to be discovered.

REFERENCES

Anderson Elaine (1968), *Fauna of the Little Box Elder Cave, Converse County, Wyoming: The Carnivora,* Colorado Univ. Studies Ser. Earth Sci. no. 6, p. 1-59.

Barr, T. C., Jr. (1961), *Caves of Tennessee,* Tennessee Div. Geology, Bull. 64, 567 p.

Cope, E. D. (1899), *Vertebrate remains from Port Kennedy bone deposit,* Acad. Nat. Sci. Philadelphia Jour., ser. 2, v. 11, p. 193-267.

Gidley, J. W. and Gazin, C. L. (1938), *The Pleistocene vertebrate fauna from Cumberland Cave, Maryland,* U. S. Natl. Mus. Bull., v. 171, p. 1-99.

Guilday, J. E. (1962), *The Pleistocene local fauna of the Natural Chimneys, Augusta County, Virginia,* Carnegie Mus. Annuals, v. 36, p. 87-122.

——— (1967a), *Notes on the Pleistocene big brown bat* (Eptesicus grandis *(Brown)*), Carnegie Mus. Annals, v. 39, p. 105-114.

——— (1967b), *The climatic significance of the Hosterman's Pit local fauna, Centre County, Pennsylvania,* Am. Antiquity, v. 32, p. 231-232.

——— (1968), *Grizzly bears from eastern North America*, Am. Midland Naturalist, v. 79, p. 247-250.

Guilday, J. E. and Adam, E. K. (1967), *Small mammal remains from Jaguar Cave, Lehmi County, Idaho,* Idaho State Univ. Mus. Jour. Tebiwa, v. 10, p. 26-36.

Guilday, J. E., Hamilton, H. W. and McCrady, A. D. (1966), *The bone breccia of Bootlegger Sink, York County, Pennsylvania,* Carnegie Mus. Annals, v. 38, p. 145-163.

——— (1969), *The Pleistocene vertebrate fauna of Robinson Cave, Overton County, Tennessee,* Palaeovertebrata, v. 2, p. 25-75.

Guilday, J. E. and Handley, C. O., Jr. (1967), *A new* Peromyscus *(Rodentia: Cricetidae) from the Pleistocene of Maryland*, Carnegie Mus. Annals, v. 39, p. 91-103.

Guilday, J. E. and Irving, D. C. (1967), *Extinct Florida spectacled bear* Tremarctos floridanus *(Gidley) from central Tennessee,* Natl. Speleol. Soc. Bull., v. 29, p. 149-162.

Guilday, J. E., Martin, P. S. and McCrady, A. D. (1964), *New Paris No. 4: A Pleistocene cave deposit in Bedford County, Pennsylvania,* Natl. Speleol. Soc. Bull., v. 26, p. 121-194.

Guilday, J. E. and McCrady, A. D. (1966), *Armadillo remains from Tennessee and West Virginia caves,* Natl. Speleol. Soc. Bull., v. 28, p. 183-184.

Hay, O. P. (1923), *The Pleistocene of North America and its vertebrated animals from the states east of the Mississippi River and from the Canadian provinces east of longitude 95°*, Carnegie Inst. Washington Pub. 499 p.

Hibbard, C. W. (1955), *Notes on the microtine rodents from the Port Kennedy Cave deposit,* Acad. Nat. Sci. Philadelphia Proc., v. 107, p. 87-97.

Jefferson, Thomas (1797), *A memoir on the discovery of certain bones of a quadruped of the clawed kind in the western parts of Virginia,* Am. Phil. Soc. Trans., v. IV, p. 246-260.

Leidy, Joseph (1889), *Notice and description of fossils found in caves and crevices of the limestone rocks of Pennsylvania,* Pa. Geol. Survey, 1st ser., Annual Rept. 1887.

Martin, P. S. (1958), *Taiga-tundra and the full-glacial period in Chester Co., Pennsylvania,* Am. Jour. Sci., v. 256, p. 470-502.

Miller, G. S., Jr. (1940), *Bones of mammals collected by Baird in Pennsylvania caves,* Jour. Mammalogy, v. 21, p. 319.

Nicholas, B. G. (1953), *Recent paleontological discoveries from Cumberland Bone Cave,* Sci. Monthly, v. 76, p. 301-305.

Patton, T. H. (1965), *A new genus of fossil microtine from Texas*, Jour. Mammalogy, v. 46, p. 466-471.

Peterson, O. A. (1926), *The fossils of the Frankstown Cave, Blair County, Pennsylvania,* Carnegie Mus. Annals, v. XVI, p. 249-315.

Ray, C. E. (1967), *Pleistocene mammals from Ladds, Bartow County, Georgia*, Georgia Acad. Sci. Bull., v. 25, p. 120-150.

Ray, C. E., Cooper, B. N. and Benninghoff, W. S. (1967), *Fossil mammals and pollen in a late Pleistocene deposit at Saltville, Virginia,* Jour. Paleontology, v. 41, p. 608-622.

Rhoads, S. N. (1903), *The mammals of Pennsylvania and New Jersey*, Philadelphia, privately published, 266 p.

Richmond, N. D. (1963), *Evidence against the existence of crocodiles in Virginia and Maryland during the Pleistocene,* Proceedings of the Biol. Soc. Washington Proc., v. 76, p. 65-68.

Schultz, C. B. and others (1963), *Paleontologic investigations at Big Bone Lick State Park, Kentucky: A preliminary report,* Science, v. 142, p. 1167-1169.

Simpson, G. G. (1941), *Large Pleistocene felines of North America,* Am. Mus. Novitiates, v. 1136, p. 1-27.

Wetmore, Alexander (1962), *Notes on fossil and subfossil birds: IV. Birds of late Pleistocene age from Augusta County, Virginia,* Smithsonian Misc. Colln., v. 145, p. 5-17.

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